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A FRAMEWORK FOR PERFORMANCE-BASED SEISMIC DESIGN APPROACH FOR DEVELOPING COUNTRIES

Ahmed ALHOURANI[1], Dang JI[2] and Takeshi KOIKE[3]

[1] Graduate student, Kyoto University,
Kyoto 615-8540, Japan, alhourani.zohir.25r@st.kyoto-u.ac.jp
[2] Research Associate, Kyoto University
Kyoto 615-8540, Japan, dang.ji.5e@kyoto-u.ac.jp
[3] Professor, Department of Civil Engineering, Graduate School of Engineering, Kyoto University
Kyoto 615-8540, Japan, koike.takeshi.7n@kyoto-u.ac.jp

A framework of seismic design method appropriate for earthquake disaster conditions of developing countries is proposed. For countries in which seismic load data is either unavailable or incomplete, a rational and simple seismic design guideline is developed utilizing the performance-based seismic design approach. For this purpose, the current seismic design practice in Syria is discussed

***Key words**: Performance-based seismic design, reduction factor, serviceability limit state, ultimate limit state, ductility factor, base shear*

1. INTRODUCTION

Many developing countries which are located near seismically active faults have suffered severe seismic disasters. Engineers in these countries expect the seismic design guideline to be appropriate and compatible with their seismic environment. In this case, occasionally UBC[1)] guideline for RC buildings in USA has been often adopted, because of its clear approach and simple usage.

In some countries, UBC guidelines are directly adopted to seismic design with only minimum revision of seismic load levels, whereas in other countries these guidelines are not always used in the correct manner. The Japanese seismic design guideline has not been adopted in developing countries, because it is not written in English and it primarily reflects the Japanese seismic conditions[2)].

Nevertheless, seismic design engineers in developing countries expect seismic design guidelines to be rational and simply applicable to their countries, where seismic load data have not yet been completely established.

When a new seismic design guideline is introduced into a developing country, the following criteria must be taken into account:

(1) The seismic design procedure is clear and easily understood;

(2) The design spectrum must be easily constructed in the way which can reflect the seismic hazard environment of the country;

(3) Safety criterion must be simply defined and its corresponding safety measure can be easily estimated; and

(4) The seismic design guideline is also simply revised when the societal and economical conditions of the country have changed in the future.

In order to develop and evaluate the new proposed seismic design approach, the current seismic method in Syria[3)] which is surrounded by major active seismic fault lines will be discussed.

2. SEISMIC DESIGN METHOD IN SYRIA

2.1 Current seismic design practice for RC buildings in Syria

Internationally two types of earthquake levels are often considered for seismic design commonly referred to as Design Basic Earthquake (DBE) and Maximum Considered Earthquake (MCE). Each earthquake level is characterized by a specific probability of exceedence (*p*), return period (T_r) and design life cycle (T_D) usually taken as 50 years. DBE is defined as the seismic event with large probability of occurrence during the design life of the structure expected to be generated by specific seismic sources in a given seismic region. MCE is defined as the most severe earthquake with low probability of occurrence during the design life of the structure. For seismic design, most codes and standards specify DBE of having 10% probability in 50 years (i.e. 475 years return period) and specify MCE of having 2% probability in 50 years (i.e. 2450 years return period) in terms of a single intensity measure such as the Peak Ground Acceleration (PGA).

The Syrian seismic design code recently published in 2004 adopts a seismic hazard map for Peak Ground Acceleration (PGA) with 10% probability of exceeding in 50 years (Return Period 475 years) as shown in Figure 1. Although this definition of the hazard map agrees with the common definition of DBE, the Syrian code does not state this fact clearly. In addition, there is no mentioning of MCE earthquake level anywhere in the code. However, it will be demonstrated in successive sections (Sec. 3.1 and 3.2) that the Syrian seismic region has the ability of generating low frequent sever earthquakes that are consistent with the definition of MCE. This supports the need of adopting a new approach that takes into account the concept of DBE and MCE.

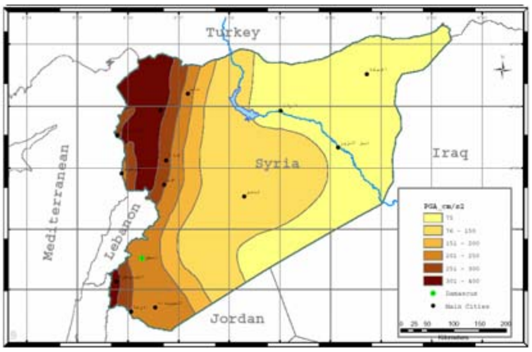

Figure 1 PGA distribution map in the Syrian seismic design code[3].

The Syrian seismic design code follows the same approach as UBC 97 which provides straight forward procedures to calculate the seismic force. Figure 2 displays the simple approach used in the current Syrian seismic design code:

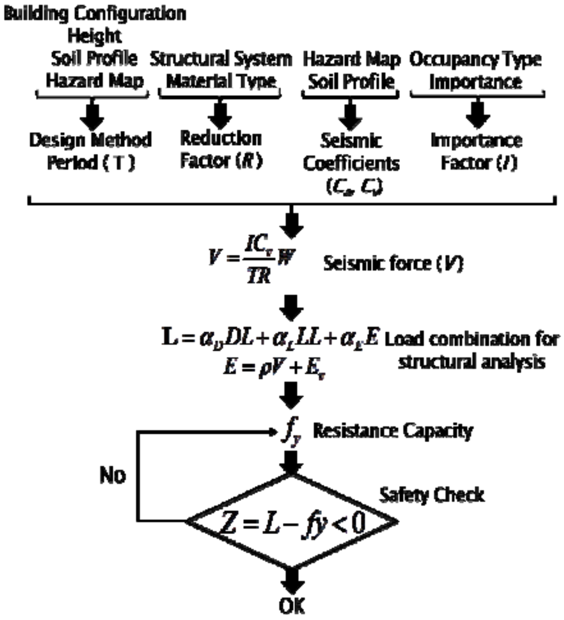

Figure 2 Flow chart of current seismic design approach in Syria

Since the safety check is assessed using the ultimate elastic yield strength, this approach is basically consistent with the serviceability limit state design method. In this case, the safety check is controlled by the capacity of the structural member. If the member is deemed inadequate to resist the resultant forces, it is necessary to increase the member's capacity by increasing either material strength or size or both.

The partial load factors α_D, α_L and α_E used in load combinations are originally calibrated from the past design practices in the USA. These factors were directly implemented in the Syrian building code with slight adjustments without considering the safety measures (i.e. probability of failure and reliability index) associated with domestic design and construction conditions.

For dynamic analysis, simplified quasi-static methods are often used to important RC buildings and infrastructures. Advanced dynamic analysis methods applied to high-rise and irregular shaped buildings such as time history analysis are briefly mentioned in the Syrian design code. Additionally, these methods are not fully understood within the Syrian engineering community and therefore rarely used in real practice.

The use of reduction factor (*R*) when calculating the seismic force *V* for elastic design, see Figure 2, is the most controversial issue in the current design approach. Although *R* in principal reflects the inelastic behavior of the structure, the value of *R* in the current code is only related to the structural lateral resisting system and building material and is taking as constant for a specific building structure as shown in Table 1.

To obtain the performance-based design framework, it is necessary to investigate the present load factors and reduction factor values in relation to structural behavior and cost efficiency and adopt more convenient values that are more suitable to the national context. The framework will provide a clear simple approach that can be used easily in practice to check the design safety for both DBE and MCE.

Table 1 Typical values of *R* for most common structural systems in Syria$^{3)}$.

Lateral Force Resisting System Description	***R***
Special Moment Resisting Frame System	**8.0**
Dual System with Special Moment Resisting Frames which are capable to resist at least 50% of Prescribed Seismic Force.	**7.5**
Dual System with Special Moment Resisting Frames which are capable to resist at least 25% of Prescribed Seismic Force.	**6.5**
Dual System with Special Moment Resisting Frames which are capable to resist at least 10% of Prescribed Seismic Force.	**5.5**
Bearing Shear Wall System without Special Moment Resisting Frames	**4.5**

2.2 Nation-wide inventory of buildings and infrastructures

The seismic design code for a certain country should be established to reflect not only seismic hazard conditions but also socio-economical conditions which are related to no. of buildings, population, GDP and other social conditions especially in major cities. The seismic design quality requirement for new structures and the seismic disaster mitigation investment for existing infrastructures should be dependent on the present capability and future development of the country.

Therefore, the most appropriate design level of PGA for Syria should be also determined from the above-mentioned national conditions with regard to seismic risk analysis and decision making of all stakeholders in Syria. Figure 3 shows a typical allocation of a city in Syria which is located along major fault lines. In order to reflect the socio-economical conditions, building inventory can be obtained as shown in Figure 4.

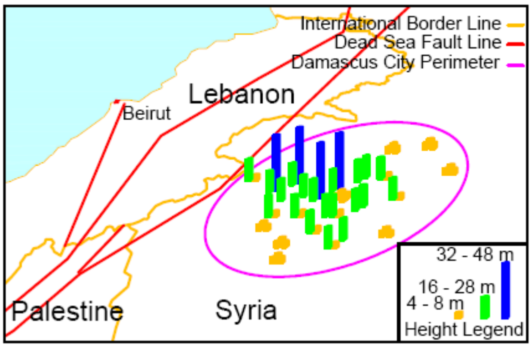

Figure 3 Residential building inventory based on height for Damascus city area.

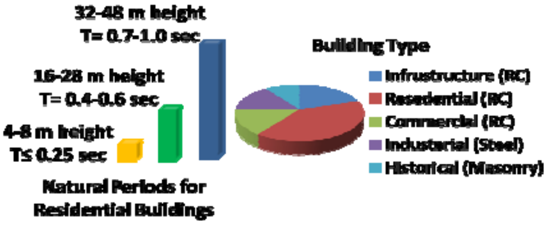

Figure 4 Building types in Syria and typical periods for residential buildings.

3. SEISMIC HAZARD ANALYSIS

3.1. History of earthquake occurrences

Syria is located on the north-western part of the Arabian plate. Major seismic sources in and around the country include; the Dead Sea Fault System (DSFS), the interplate Palmyrides shear zone, East Anatolian fault system south of Turkey and the north Anatolian-Zagros fault system north west of Iran as shown in Figure 5.

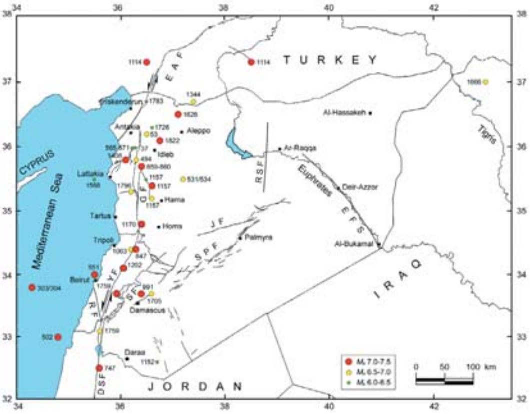

Figure 5 Major seismic sources and historical earthquake in Syria[4].

Instrumental recording of seismic activity in Syria initiated in 1995 with the establishment of the Syrian National Seismological Network (SNSN)[5]. Most seismic events are concentrated on the Syrian west coast along the DSFS on the margins of the Arabian plate. Most recorded seismic data indicates dominance of low magnitude earthquakes (M<5). Moderate earthquakes (6≤M ≤7) are scarce. There is no recorded major earthquakes (M>8) after the initiation of the SNSN in 1995. The largest local recorded earthquake was on December the 24, 1996 in Palmyrides belt region with a magnitude of 5.6. Moderate earthquakes in Japan are more frequent and at least three major earthquakes happened in Japan since 1995.

Well documented historical records display that the Syrian region has been affected in the past by many large earthquakes that occurred along the DSFS[4] as shown in Figure 5. The magnitude of these events ranges from 6.0-7.9 and the time interval between these events along each segment ranges from 200 to 1000 years. The seismic quiescence along the fault system segments could produce a major earthquake with major consensus to the population centers of Syria and Lebanon.

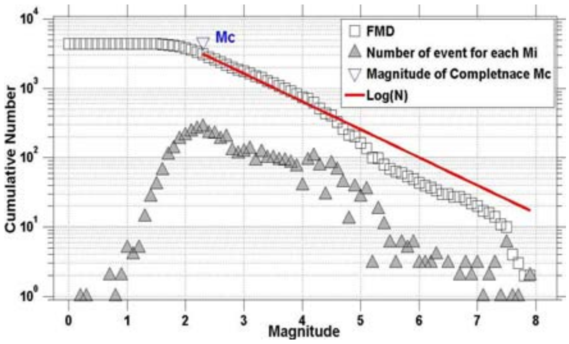

Figure 6 The cumulative frequency magnitude distribution for Syria and surrounding seismic regions.

In order to understand the seismicity nature of Syria, a seismicity study was conducted by the authors to produce the frequency magnitude distribution (FMD) for Syria and surrounding seismic regions using an open source tool ZMAP[6] (The software used for this study can be freely downloaded from; http: // www. seismo. ethz.ch/staff/stefan). A seismic catalog containing historical and instrumental seismic records from 37 to 2011 AD was compiled for this study. The FMD curve for Syria is presented in Figure 6. FMD is mathematically expressed using the Gutenberg-Richter recurrence relationship:

$$\log(N) = a - bM \tag{1}$$

where N is the number of events with magnitude Mi greater than some threshold M. b *and* a are log linear constants. The seismicity study for Syria and surrounding seismic region gives the following values for constants a and b:

$$a = 4.43 \quad , \quad b = 0.403 \pm 0.006$$

Assigning the appropriate return period and probability of exceedence for each level of earthquake (*DBE, MCE*) depends entirely on the frequency magnitude relationship for a specific region. The return period for a certain probability of exceedence during the design life cycle of a structure is determined using the following equation:

$$p = 1 - \left(1 - \frac{1}{T_r}\right)^{T_D} \tag{2}$$

The seismicity study for Syria and surrounding seismic region indicates that moderate highly frequent earthquakes ($5 \le M_W \le 6$) have a return period of ($360 \le T_{r,\,DBE} \le 960$ yrs) with probability of exceedence of ($13\% \ge p_{DBE} \ge 5.1\%$) during 50 years of design life cycle. On the other hand major low frequent earthquakes ($7 \le M_W \le 8$) have a return period of ($2475 \le T_{r,\,MCE} \le 6215$ yrs) with probability of exceedence of ($2\% \ge p_{MCE} \ge 0.8\%$) during 50 years of design life cycle. These values coincide very well with the common definition of DBE and MCE used in most international seismic design codes.

In Syria, like in other developing countries, lack of full scale studies of the tectonic mechanism and features of the major seismic sources, lack of strong motion records for major earthquakes and the lack of understanding of advanced dynamic methods in seismic analysis amongst the engineering community are major difficulties facing the adoption of the concept of DBE and MCE in seismic design.

3.2 GIS mappings of PGA

PGA hazard map in Syria shows comparatively large acceleration especially at the western region along the Syrian coastline reaching 400 gals shown in Figure 1. These values are almost similar to that in Japan because of the high seismicity of Syria and surrounding region.

Limited studies are available for assessing the seismic hazard map for Syria. These studies use probabilistic methods with either line source models7),11) or area source models8),12) assuming bed rock for ground conditions. At present, the soil classification map for Syria is not available. The hazard maps produced by those studies correlate very well with the hazard map adopted by the Syrian code.

The attenuation relationship of PGA for a specific probability of exceedence (level of earthquake) and site is essential for the evaluation of the proposed performance based design framework. The following attenuation equation is commonly used to express PGA in terms of magnitudes (*M*) and hypocentral distances (*D*)9):

$$PGA = b_1 e^{b_2 M} (D + 25)^{-b_3} \qquad (3)$$

The following values are assigned to the constants b_1, b_2 and b_3 for Syria and surrounding seismic region7):

$$b_1 = 837 \quad , \quad b_2 = 0.89 \quad , \quad b_3 = 1.73$$

3.3 Design response spectra

In seismic design procedures, two types of earthquake loads must be prepared; those are the design basic earthquake (DBE) and the maximum considered earthquake (MCE).

The seismic load of DBE can be given by the response spectrum in the following form:

$$S_A(T) = \beta_A(T) \cdot PGA = \beta_A(T) \cdot \gamma_{soil}(T_G) \cdot PGA_{base-rock} \qquad (4)$$

in which $\beta_A, \gamma_{soil}, PGA_{base-rock}$ are the normalized response spectrum by input acceleration, surface amplification factor and peak ground acceleration at the base-rock, respectively.

There is uncertainty in the response spectrum which comes from the uncertainty of the PGA predicted by the attenuation formula, and that of the amplification factor of the surface layer.
In order to reflect the uncertainties of DBE in the response spectrum, two set of the design response spectrum10) shown in Figure 7 is proposed, where the upper curve is generated as the 90% non-exceedence level of the envelope curve, and lower curve is as the 70% of it. Once these two curves, the statistical parameters at the response spectrum is calculated as follows:

$$E\left[\ln S_A^{EQ2}\right] = \ln S_A^{90} / \left\{1 + \mathrm{cov}\left(\ln S_A^{EQ2}\right) \cdot \Phi^{-1}(0.9)\right\},$$
$$E\left[\ln S_A^{EQ2}\right] = \ln S_A^{70} / \left\{1 + \mathrm{cov}\left(\ln S_A^{EQ2}\right) \cdot \Phi^{-1}(0.7)\right\} \qquad (5)$$

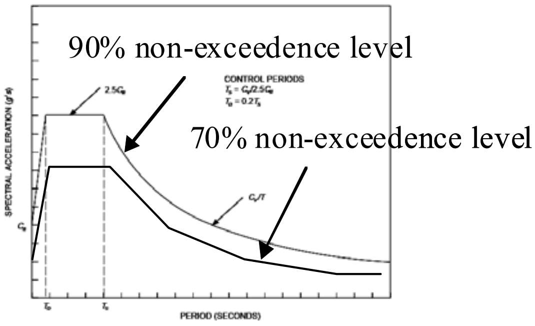

Figure 7 Design response spectra for dual exceedence levels.

The generation of design earthquake wave for MCE level seismic events, on the other hand, can be proceeded by a few ways. Although semi-empirical methods11),12),13) which presume the source rapture and cumulate waves from source to site by considering distance attenuation, are available to date, it is still difficult to put these methods into general design practice in developing countries. Therefore, as a basic approach to serve MCE level design earthquake waves, the methods by generating waves from white noise or seed recordings are recommended.

Considering the difficulty of real usable records in developing countries, historically recorded accelerogram such as El-Centro wave is used as a sample wave hereafter. In actual design stage, earthquake data recorded in the Syrian region should be used as seed waves.

4. PERFORMANCE-BASED SEISMIC DESIGN APPROACH

4.1 Seismic design formulation with the design response spectrum

The proposed seismic design method is formulated based on the limit state design method, in which the seismic safety for serviceability limit state can be assessed as the probability that random load combination $\mathbf{L}^S$ of dead *DL*, live *LL* and seismic effect *E* exceed the capacity limit $\mathbf{R}^S$ in the following way.

$$p_f^S = P\left[Z^S < 0 \middle| DBE\right] = \Phi\left[-\frac{E\left[Z^S\right]}{\sqrt{Var\left[Z^S\right]}}\right] \tag{6}$$

in which

$$\mathbf{Z}^S = \mathbf{R}^S - \mathbf{L}^S \tag{7}$$

$$\mathbf{L}^S = DL + LL + E \tag{8}$$

and the capacity limit is given by the yield strength.

In the same way, the seismic safety for the ultimate limit state is also evaluated as the probability that inelastic seismic response $\mathbf{L}^U$ exceeds the capacity displacement limit $\mathbf{R}^U$ in the following way.

$$p_f^U = P\left[Z^U < 0 \middle| MCE\right] = \Phi\left[-\frac{E\left[Z^U\right]}{\sqrt{Var\left[Z^U\right]}}\right] \tag{9}$$

in which

$$\mathbf{Z}^U = \mathbf{R}^U - \mathbf{L}^U \tag{10}$$

In the Syrian seismic design guideline, the seismic load is also a combination of horizontal load and vertical load such as

$$E = \rho V + E_v \tag{11}$$

where V, E_v, ρ are base shear, vertical seismic load and the control parameter, respectively. The base shear[14)] can be formulated as an inertia force

$$V = S_A(T) \cdot W / g \tag{12}$$

in which $W, S_A(T), T, g$ are the total dead load, , response spectrum, typical period of the structural system and gravity constant, respectively.

4.2 Seismic risk analysis for the optimal parameters

The capacity limit for DBE must be assessed to fulfill the seismic performance for the serviceability limit state. The optimal solution for this request can be obtained by using the seismic risk analysis[15)] such as

$$C^S = C_S^S + n^S p_f^S \cdot C_{EQ}^S \tag{13}$$

in which

C_S^S : retrofit investment for existing structures for minor damage mode

C_{EQ}^S :repair cost for minor damage

n^S : expected number of excessive minor damages during service period (T_D)

If this analysis is applied for all the structural assets in a target city, the expected risk can be evaluated by the following formula.

$$E\left[C^S\right] = C_S^S + n^S \int_{Area} \nu_{Building}(x) \int_0^{C_{\max}} p_f^S(u,x) f_{C_{EQ}^S}(u)\, du\, dx \tag{14}$$

in which $\nu_{Building}, C_{\max}, f_{C_{EQ}^S}$ are the damage rate of the building per unit area, the maximum cost for the inelastic structural response and the probability density function of the restoration cost as shown in Figure 8 which is a schematic illustration of the restoration cost for various structural responses of the yield and maximum displacements.

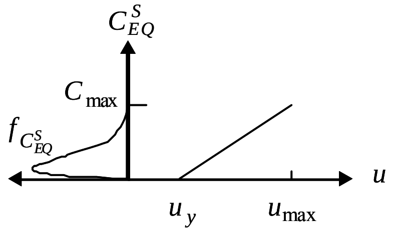

Figure 8 Seismic restoration cost for inelastic response of the main structural component.

The probability of density function $f_{C_{EQ}^S}$ is defined between two fixed boundary of $[0, C_{\max}]$. So the Beta probability density function is introduced to describe its statistical characteristics in the following way:

$$f_X(x)=\frac{1}{B(q,r)}\frac{(x-a)^{q-1}(b-x)^{r-1}}{(b-a)^{q+r-1}} \qquad a\le x\le b \tag{15}$$

where *q, r* are parameters to control the profile of the probability density function.

$$B(q,r)=\frac{\Gamma(q)\Gamma(r)}{\Gamma(q+r)} \tag{16}$$

and

$$P[x_1 < X \le x_2]=\frac{1}{B[q,r]}\left[B_u(q,r)-B_v(q,r)\right] \tag{17}$$

in which

$$B_z(q,r)=\int_0^z y^{q-1}(1-y)^{r-1}dy \qquad 0<z<1 \tag{18}$$

$$u=\frac{x_2-a}{b-a} \quad , \quad v=\frac{x_1-a}{b-a} \tag{19}$$

Generally the disaster mitigation or retrofit investment increases with higher resisting capacity f_y as shown in Figure 9. But the probability of failure will be decreased for increasing resisting capacity shown in Figure 9.

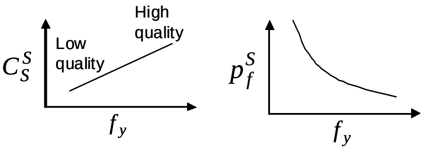

Figure 9 Schematic illustrations of Seismic disaster prevention cost and its corresponding probability of failure in serviceability limit state for various structural capacities.

4.3 Optimal yield capacity for serviceability limit state

The flow chart shows how to obtain the optimal capacity limit f_y^* for DBE once the target probability $p_f^{S,\text{target}}$ and several cost data, C_S^S, C_{EQ}^S, are given in Figure 10.

For a given design response spectrum, seismic load is calculated as a random value of load combinations. The optimal solution of the yield capacity is estimated from the minimum value of the cost which is obtained from the seismic risk analysis of Eq.(13).

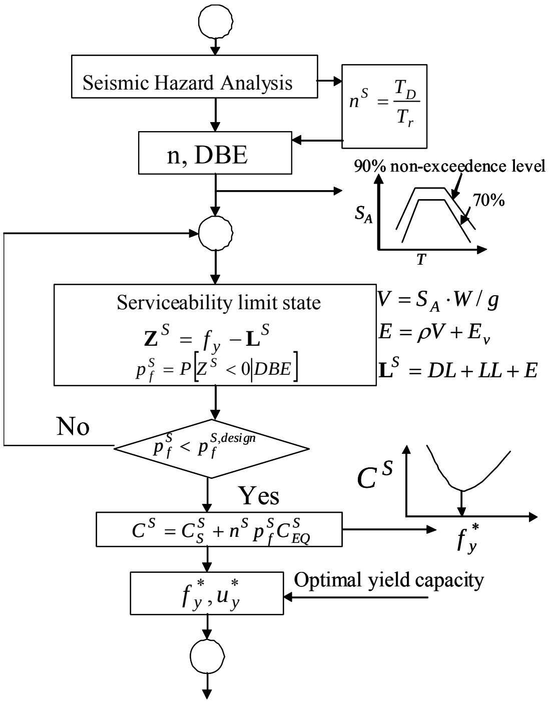

Figure 10 The flow chart to estimate the optimal structural capacity for serviceability limit state.

4.4 Optimal displacement capacity for ultimate limit state

The flow chart of Figure 11 illustrates how to obtain the optimal ultimate capacity limit for MCE in the same way as shown in Figure 10.

The ultimate limit is measured by the response displacement of the structural system. By using a single degree of freedom system with the fixed yield capacity, f_y^*, and a single earthquake accelerogram of MCE, the optimal maximum displacement capacity, u_m^*, is derived as the value corresponding to the minimum cost which is derived in the similar manner from the seismic risk analysis of Eq.(13). And the yield strength reduction factor14), R_y^*, is also obtained as

$$R_y^*=\frac{f_0}{f_y^*} \tag{20}$$

where f_0 is the maximum force value of the elastic response for MCE, and f_y^* is the optimal capacity limit for DBE shown in Figure 10.

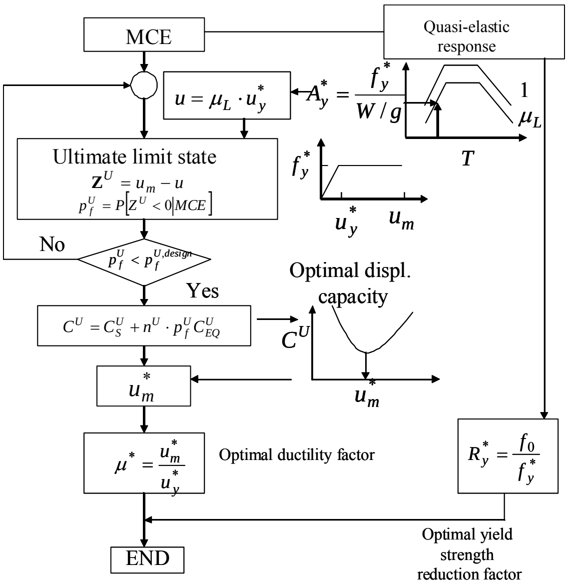

Figure 11 The flow chart to estimate the optimal deformation capacity for ultimate limit state.

Since the optimal maximum deformation u_m^* is estimated in the flow chart of Figure 11, the optimal ductility factor is also given by

$$\mu^* = \frac{u_m^*}{u_y^*} \tag{21}$$

in which the inelastic response spectra in Figure 12 plays an important role.

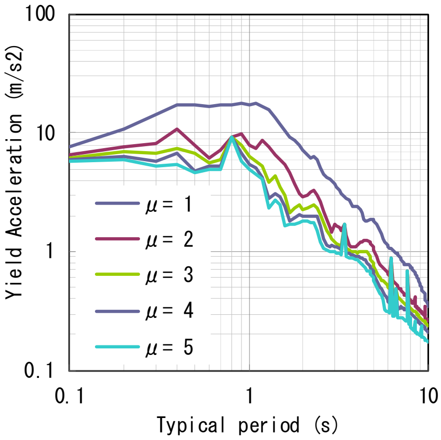

Figure 12 The elastic and inelastic response spectra

4.5 Reevaluation

The proposed performance-based framework based on seismic risk analysis will provide rational estimation of the optimal yield strength reduction factor (R_y^*) that takes into account the local seismic hazard environment and socio-economical conditions in the developing country. Reduction factors used in the Syrian seismic design code should be compared to the optimal yield strength reduction factors produced by the proposed framework.

The $R_y^* \sim T$ relationship between optimal yield strength reduction factors and natural periods for various probabilities of exceedence (p) of MCE could be generated through the proposed framework. If the optimal yield acceleration is given, for instance, by

$$A_y^* = f_y^* /(W/g) = 500\ gal$$

, the $R_y^* \sim T$ relationship is illustrated in Figure 13.

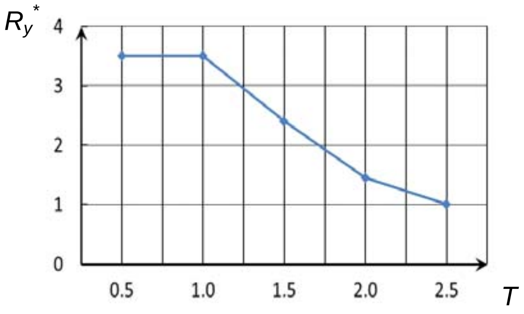

Figure 13 Illustration of $R_y^* \sim T$ curve.

In Table 1, the reduction factor provides a larger value for a building with higher ductility which is related to a longer typical period *T*. But the figure 13 shows that a building with the same longer typical period *T* decreases the value of R_y^*. This contradictory result suggests that the present reduction factor used in Syria should be reevaluated on the basis of the rational approach proposed herein. (Note: Just to clarify that it is hard to compare the results of R_y^* with that of Table 1, because in Table 1 there is no consideration to the natural period in the selection of *R*. For example if I have two RC buildings with Special Moment Resisting Frame System used in both buildings to resist lateral loads, if one of the buildings is 5 stories high and the other is 14 stories high both buildings would be assigned a reduction factor of 8 no matter what the value of the natural period of both buildings. This is one of the problems of using Table 1; there is no connection between the buildings dynamic properties (frequency or period) and the real value of *R*. If this is what meant in the paragraph so it is very accurate)

5. CONCLUSIONS

Due to current advances in probabilistic methods for hazard and risk analyses, it is desirable for developing countries to adopt more advanced and reliable approaches for seismic design. The proposed framework utilize the use of probabilistic methods in the form of probabilistic distribution functions for cost and damage estimation to generate more reliable data to be used in seismic design. The clear and coherent flow of the proposed framework makes this approach easy to understand and apply in developing countries.

The following are most likely advantages of using the proposed performance-based design framework:

- Modifying or/and upgrading the seismic design practices in developing countries through proposing a clear and simple approach. This approach will increase the structural performance (reliability) under different earthquake hazard levels and also increase the level of confidence in using advanced seismic design methods within the engineering communities in developing countries.

- A rational estimation and usage of the reduction factor *R* used in Syria should be compared and implemented with the yield strength reduction factor proposed by N. Newmark.

- According to seismic hazard assessment in Syria, the occurrence of MCE is genuine. The proposed approach offers a more accurate assessment of seismic design force that considers all possible hazard levels.

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