APPLYING VALUE ANALYSIS IN DESIGN OF ISOLATED STRUCTURES

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ABSTRACT

In an optimal seismic design, structural performance should be in a balance with other variables which form the design space. In practice, such a balance can be achieved by using the value analysis in which cost-benefit analysis methods are often applied to assess the value. To develop regulations by which the optimal performance is directly obtained by the value analysis, study structuralsystems from the cost-benefit point of view is essential. In the present research by employing the value analysis, the optimal performance of the isolation system for low-rise frame structures is studied. Firstly, a design framework is proposed in which the main design variables in cost-benefit analysis of structures are taken into account. Then, using this framework indifferent case studies, the optimal performance of the isolated structures is identified under different design situations. In each case, besides the isolated structures, the same structures with fixed bases are analysed. The results show how the optimal performance varies with respect to variation in occupancy type, design life period, and also economic environment. One of the main results shows that the use of the seismic isolation is not justifiable for structures with residential occupancy.

INTRODUCTION

The cost-benefit analysis is an efficient tool for the value assessment in a structural design problem. In the recent years, various frameworks have been proposed to evaluate the performance of a structural design under seismic loads from cost or cost-benefit point of view (e.g., Wen and Kang, 2001, Sanchez-Silva and Rackwitz, 2004, Goda and Hong, 2005, Taflanidis and Beck, 2009). Despite the general similarities between the existing frameworks, most of them are merely based on cost analysis methods and role of benefit as the inherent part of the value analysis has not been considered. Moreover, in the carried out studies, comprehensive approaches are not often applied to account for all the influential variables in cost-benefit analysis. For instance, the effect of the design life span and economic environment as the important variables in cost-benefit analysis has been considered in only few studies (Wen and Kang, 2001, Sanchez-Silva and Rackwitz, 2004).

The use of value analysis becomes more important in relation to design of structural systems such as base isolation. In base isolation technique, performance of structure is significantly improved, but cost of construction increases in comparison with cost of conventional systems. To find the optimal performance for isolation system, different cost aspects such as construction and life cycle costs should be integrated into a cost-benefit analysis. However, only few of studies have considered the cost-benefit issues related to the analysis and design of isolation system (e.g., Goda and Hong, 2010). On the other hand, the aim in the existing method for design of isolated structures is to provide a high-level of the structural performance (Naeim and Kelly, 1999), while the high performance level may not be necessarily the optimal solution for the design of isolated structures from the value-based point of view.

In the present research, a comprehensive framework based on the cost-benefit analysis is proposed in which the most influential variables are incorporated. These variables are structural performance, occupancy type, design life span and discount rate. Applying the proposed framework in three case studies, a four-story building structure of five different configurations in superstructure with and without base isolation is analysed under various situations. The same structure with fixed base is also studied in order to find the cases where the employment of the base isolation system has more justification than the conventional fixed-based system. The structural configurations are designed such that to span a wide performance range from very low to very high. For cost-benefit analysis of both fixed and isolated structures, two occupancy types of residential and hospital are selected to represent respectively the ordinary and special applications. Also, three design life spans of 2, 50 and 100 years are considered respectively as short, medium and long term operational durations; as well as four discount rates of 1% to 4% to represent economical environments with slow to rapid growths.

Value-based design framework

Value analysis requires a framework in which the main parameters in cost-benefit analysis are accounted for. These parameters are recognized as structural performance, occupancy, design life span and discount rate. To apply the value analysis in the optimal design, it is firstly necessary to define a measure for the value.The value measure as a decision-making parameter in seismic design is defined often by the comparing between cost and benefit (e.g., inSanchez-Silva and Rackwitz, 2004). The value measure can be defined by the following expression:

$$V = (B - C) / C_C \tag{1}$$

in which V is the value measure of the design,Brepresent the total net benefit to the owner from renting the building over the design life span,C_C is the construction cost and$C$is the cost of the building during its design life span. The estimation of B and C is based on the value of money at the beginning of the design life span.
The cost of the building during its design life span consists of the following cost items:

$$C = C_M + C_E \tag{2}$$

whereinC_M is the maintenance cost andC_E is the cost due to the earthquake damage. The cost items in Eq. (2) are distributed over the design life span.The construction cost is sum of various costs and expenses related to material, labor, machinery, management and overhead. The total construction cost is divided into cost of structural and non-structural elements. Based on the existing construction cost data for buildings with different occupancies (Taghavi and Miranda 2003), cost of non-structural elements are usually more than cost of structural elements.

Maintenance cost of the building includes costs related to inspection, repair or replacement of non-structural and structural elements under operational conditions. If the maintenance cost is assumed to be uniformly distributed over the design life span, it can be expressed as follows:

$$C_M = \int_0^{T_D} C_m \ f(t, \lambda) \ dt \tag{3}$$

in which, C_M is the maintenance cost, C_m is the annual maintenance cost, T_D is the design life span,λ is the annual discount rate and f is a function to discount future costs. The discounting on the future costs is necessary to scale costs to the time of construction. Discount rate can be used as the difference between return rate and the inflation rate.

Structures in their design life span are subjected to a variety of earthquake hazard intensities from weak to severe. Characteristically, weak earthquakes have high occurrence rate and are less probable to cause damage; but severe earthquakes are capable to cause serious damage despite that their occurrence rate is very small. To quantify the earthquake damage, both intensity-occurrence and intensity-damage models are required. With combination of these two models and summing the probable damage costs over all the intensity levels, the earthquake damages cost can be obtained.

To express the time distribution of the earthquake occurrence, a forecasting model is needed. Poisson distribution is a classic model for expressing the earthquake occurrence probability in time. In this model, with the assumption of time and space independency between events, the probability of events with average return periods greater than T_R in time period of t is expressed as follows:

$$P(t,T_R) = 1 - e^{-t/T_R} \tag{4}$$

In seismic hazard analysis factors such as magnitude,distance from fault and soil condition are involved. Since the explicit relation between these factors is not always available, in design procedures it is generally accepted to use the earthquake spectrum to express the intensity of earthquake. The earthquake spectra are often defined as a function of peak ground acceleration and soil condition at site. For design of building structures, the spectrum is usually defined corresponding to an intensity which the average return period of occurrences with intensities equal or greater than that is 475 years.

To estimate the earthquake damage in different intensities, a clear relation between the scale of the spectrum and the return period is needed. The simple model in the form of Eq.(5) can be used to scale a spectrum corresponding to return period of 475 years to another spectrum corresponding to return period of T_R.

$$S_{T_R} / S_{475} = (T_R / 475)^m \tag{5}$$

In above Equation, S_{475} is the spectrum corresponding to return period of 475 years, S_{TR} is the scaled spectrum corresponding to return period of T_R and m is a constant. In some seismic codes (e.g. ASCE-41), models similar to the one in Eq. (5) are proposed for scaling the earthquake spectrum in which m is selected based on tectonic conditions of the site. If $T_{R,\min}$ is considered as the minimum return period corresponding to the minimum intensity capable to cause damage and $T_{R,\max}$ as the maximum return period corresponding to the maximum physically possible intensity, the range of interest for the estimation of the earthquake damage cost falls between $T_{R,\min}$ to $T_{R,\max}$.

In an analytical approach to the estimation of the earthquake damage cost, each damage type may be considered as a function of interstory drift or floor acceleration or both depending on the occupancy type of the building. If C_{ET} represents the damage cost corresponding to intensity of S_{TR}, it can be expressed as the sum of costs due to drift and acceleration.Earthquake damage cost includes mainly the costs of damage to structural and non-structural elements, contents, user's life and costs due to out of service.

Having damage costs estimated for different intensities, C_{ET} can be formed as a damage-intensity curve (Figure 1). The maximum cost in a damage-intensity curve is corresponding to cost due to collapse of the building. All the characteristics of the building related to structural performance and occupancy are reflected in the damage-intensity curve. Having damage-intensity curve and probability density function of earthquake occurrences, the expected cost of earthquake damage can be obtained by cumulative sum of probable earthquake damages over the design life span:

$$C_E = \int_{T_{R,\min}}^{T_{R,\max}} \int_0^{T_D} C_{ET}\; f(t, {}^{a})\, p(t,T_R)\, dt\, dT_R \tag{6}$$

inwhichC_E is the expected earthquake damage cost caused by all the intensities corresponding to return periods between $T_{R,\min}$and$T_{R,\max}$ for a building structure over its design life span.

In Figure 1, the cumulative damage-intensity curve for intensities with return periods between $T_{R,\min}$ and $T_{R,\max}$ are schematically depicted. Unlike the damage-intensity curve which is only a function of the structural performance and occupancy, the cumulative damage-intensity curve is also a function of design life span and discount rate. The cumulative damage-intensity curve reflects the contribution of all intensities considering their damage cost and probability of occurrences.

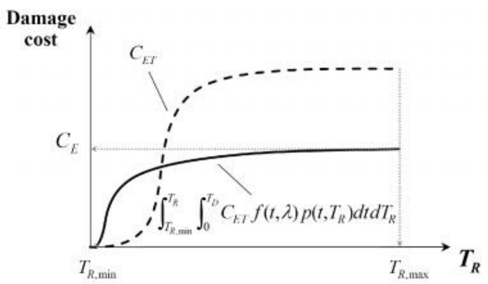

Figure 1.schematicdamage-intensity and cumulative damage-intensity curves for a building structure

The benefit that a building has for its owner is equal to amount of rental income during the design life span. Including the loss of incomes due to out of service caused by the earthquake damage, the total benefit over the design life span of the building can be expressed as follows:

$$B = B_D - B_L \tag{7}$$

in which B is the netincome, B_D is the grossrental income and B_L is the loss of income in out-of-service times.Assuming that the annual rental increase rate is equal to the inflation rate, $B_D$can be estimated through the annual rental rate at the beginning of the life span times the number of life span years.Having out-of-service times as a curve for different damage intensities, $B_D$can be obtainedby a procedure similar to one for the estimation of C_E.

By the framework described above, the value measure can be obtained as the function of structural performance, occupancy, design life span and discount rate. If the value measure is considered as the function of the structural performance represented by a structural design parameterwhile the other three factors remains unchanged, a schematic value curve such as the one depicted in Figure 2 can be obtained.

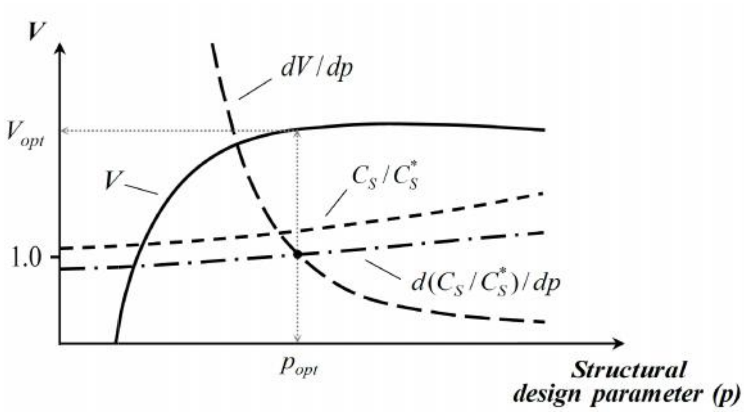

Figure 2.The schematic curves for determination of optimal value

As the structural design parameter increases, the earthquake damage cost decreases and consequently the value measure is improved; but the rate of improvement gradually decays(Figure 2). On the other hand, cost of earthquake resisting partin the structural system, C_S, increases as the design parameter increases. Unlike the value curve, the rate of C_S increases as the design parameter increases. If $C_S$is normalized by the cost of the earthquake resisting partcorresponding to minimum earthquake load, C_S^*, an optimal design parameter can be found at which the rate of $C_S / C_S^*$and the rate of$V$ are equal(Figure 2). In the range lower than the optimal design parameter,additional investment on the structural system returns more improvement in the value;but forthe range higher than the optimal parameter, more investment on the structural system results in less improvement in the value.The determination of the optimal performance based on the variation of rates that described here is conceptually different from the methods in which the optimal performance is derived by the minimization of the total cost (e.g., in Wen and Kang, 2001) or maximization ofthe benefit minus the total cost (e.g., in Sanchez-Silva and Rackwitz, 2004).

Case studies on optimal design of isolated structures

In the study, a four-story isolated structure is selected for which five alternative configurations are considered; also, the same structures with fixed bases are considered besides the isolated ones. Through the value analysis in three case studies, the optimal performance is identified while other design variables are changed. The structure in both systems is a steel frame with symmetric 16×16 m plan which contains four bays each of length 4.0 m and four stories each of height 3.3 m. Two braced frames in each principal direction of the plan resist about half of the lateral inertial force. The structural responses obtained from the two-dimensional models of the braced frames are considered as the global responses of the corresponding three-dimensional structures.

In the analytical modelling, connections of beams are considered to have low flexural stiffness. With the assumption of lumped plasticity, columns and braces are modelled by elastic elements which are connected with yielding zero-length link elements at the ends. A bilinear elasto-plastic hysteretic behaviour is selected for the flexural yielding link elements in columns.The shear stiffness of the link elements at isolation layer are assigned such that the isolation period is 2.2 s. The structural modelling is carried out by the OpenSees software.

The structures considered for the study are designed according toUniform Building Code 97 (UBC 97) based on static force procedure forfixed structures. These structures are labelled from S1 to S5 that are designed forsoil type of C and peak ground acceleration of 0.40 g with different importance factors (Table 1).The structure S1 has a very low capacity to withstand earthquake loading. The structure S2 has more capacity than S1 but does not meet the minimum capacity required by the code. The structure S3 and S4 satisfies the code requirements for design of structures with ordinary and special occupancies, respectively. The structure S5 is over-designed and is not recommended by the code. With the selected importance factors, a wide range of performance for both fixed and isolated structures are covered. Applying an eigenvalue analysis, the vibration period of the first mode of the structures with fixed and isolated bases are obtained that are given in Table 1.

Table 1.Design and cost data related to the structural configurations in the case studies

structure	importance factor	1st mode period (s)		C_S (10^5 USD)		C_C (10^6 USD)		C_E (10^6 USD)	
		Fx	Is	Fx	Is	Fx	Is	Fx	Is
S1	0.4	1.00	2.31	0.39	1.38	2.16	2.26	32.06	4.17
S2	0.7	0.85	2.26	0.44	1.76	2.18	2.31	4.57	0.95
S3	1.0	0.74	2.24	0.55	2.21	2.20	2.37	2.17	0.52
S4	1.3	0.67	2.22	0.69	2.84	2.29	2.51	1.32	0.32
S5	1.6	0.61	2.21	0.83	3.64	2.38	2.66	1.04	0.20

The structural costs of S1 to S5 are assumed to be as in Table 1. For the fixed structures S4 and S5, relatively larger costs are assigned because they may need special foundations (e.g., pile foundation) to support large axial column forces. To include the cost of isolating, the costs for the isolated structures are assigned larger than the ones for the fixed structures. It is assumed that the isolators installed at the base of structures with higher indices are designed to undergo larger deformations; as a result, the isolation costsare assigned proportional to the structural performance.

Two occupancy types of residential and hospital are selected to study the impact of the ordinary and special occupancy types on the optimal design. In a building with hospital occupancy, the value of the non-structural components and contents is significantly higher than those in a residential building; additionally, the density of occupants is higher. Moreover, unlike the residential occupancy, the activity of a hospital is related to human life; as a result, the loss due to business interruption of a hospital is much higher than a residential building. In the study, the mentioned variables are assigned by reasonable values selected based on the values presented in (Kang and Wen, 2000).

Three design life spans of 2, 50 and 100 years are considered to study the impact of short, medium and long range design life spans. The construction costs for different occupancies are selected based on the cost data provided in 2012 Building Construction Cost Data. The construction cost of the building with structure of S3 residential and hospital occupancies are assumed to be equal to 200 and 300 USD/ft^2, respectively. The difference between these costs is associated with cost of non-structural elements which is significantly higher in the hospital occupancy. The construction costs of the buildings with residential occupancy are given in Table 1.To model economies with different growth rates, four discount rates of 1, 2, 3 and 4% are selected. At higher discount rates, the life-cycle costs are more discounted.

To construct the damage-intensity curve (i.e., C_{ET}), incremental dynamic analysis is applied with selecting various return periods. The return periods of 9 and 9975 years are respectively assumed to be $T_{R,\min}$ and $T_{R,\max}$. The earthquake spectrum recommended by UBC 97 is selected as the spectrum corresponding to the return period of 475 years. To obtain other spectra at different return periods, Eq. (5) with exponent of 0.5 is used. To apply the nonlinear time-history analysis, the three spectrum-matched acceleration records of El Centro, Taft and Hachinohe are applied. A total number of 225 analyses are performed for each fixed or isolated systems. In each analysis, the maximum interstory drifts and floor accelerations are determined; then the averaged values of drifts and accelerations are calculated between the maximum values that are used in damage functions to obtain the damage costs.

The total damage to the building is broken into damages to the stories. The damage function for all the damage types in a story is assumed to be mathematically a power curvein termsofperformance parameters (i.e., drift or acceleration). This curve falls betweentwo extreme limits of the performance parameter at which the story contains no damage and the damage is complete due to collapse of the story. In the interval between these two limits, the damage is determined by a power function with exponent of *r*.

For the damage functions related to drift, the extreme limits are 0.4% and 5% respectively; for the ones related to acceleration, the lower and upper limits are respectively taken equal to 0.5 g and 2.0 g. In the estimation of the total damage, it is assumed that the damage in all stories is complete, if one of the stories reaches to its collapse drift (i.e., 5%). Also, it is assumed that the damage is complete, if one of the columns reaches to its buckling load. To assign reasonable values to *r* for different damage types, the discrete damage data related to different damage states provided by Kang and Wen(2000) are used; also, the required costs per unit area and time are selected based on data given by Kang and Wen (2000). Applying a spline interpolation through the damage costs obtained at different return periods, C_{ET} is estimated for all the return periods between $T_{R,\min}$ and $T_{R,\max}$. Through the Eq. (6), the expected earthquake damage cost is obtained. The earthquake damage cost for fixed and isolated systems with residential occupancy, life span of 50 years and discount rate of 0% is given in Table 1. The discount rate of 0% means that no discounting is applied on the time-distributed costs.

The optimal importance factors and also the optimal values obtained for both residential and hospital occupancies with life span of 50 years and discount rate of 0% are presented in Table 2.

Table 2. The obtained design parameters with discount rate of 0% and life span of 50 years

Occupancy	I_{opt}		V_{opt}		$(V_{opt,Is} - V_{opt,Fx}) / \lvert V_{opt,Fx} \rvert$	R_S	
	Fx	Is	Fx	Is		UBC 97	Prop. method
Residential	0.98	0.57	4.12	3.90	− 0.05	0.82	0.58
Hospital	1.18	0.79	2.03	3.27	0.61	0.66	0.67

It is seenthat the optimal importance factors for isolated structures are lower than the ones for the corresponding fixed systems in both occupancies.It should be noted that the optimal importance factors obtained for the isolation system are based on the design procedure of the fixed system that is different from the separate static procedure recommended in UBC 97 in which the response modification factor is limited to values not higher than 2.0 and the importance factor for all occupancy types are considered equal to 1.0.

For the both structural systems, the optimal performance increases as the occupancy varies from residential to hospital (Table 2). Recommended importance factors by UBC 97 for the fixed systems with residential and hospital occupancies are respectively equal to 1.0 and 1.25 which agree with the obtained results.The optimal factors for the residential occupancy are obtained lower than the ones for the hospital occupancy. To make a comparison between the design base shear recommended by UBC 97 with the optimalones by the proposed method,the design shear coefficient (i.e., design base shear divided by the effective dead weight) are calculated for the fixed and isolated structures. For the both occupancies, the ratiosof the design shear coefficientof the isolated system to the fixed one, R_S,obtained by UBC 97 and the proposed method are presented in Table 2.For the hospital occupancy the obtained ratios are close to each other; but they are apart for the residential occupancy. This is because of limitations imposed by UBC 97 on importance factor and response modification factor in the design procedure of the isolation system.

The optimal values given in Table 2 show that for the residential occupancy, the application of fixed system provides higher value than the one by the isolation system; while, opposite is true for the hospital occupancy in which the higher value is provided by the isolation system. The relativedifference of the optimal values calculated between fixed and isolated systems in Table 2 adequately show that applying the isolation system for the residential occupancy has no strong justification.

The values obtained for design life spans of 2 and 100 years are presented in Table 3. It is seen thatthe optimal importance factors for life span of 2 years are lower than the ones for life span of 50 years; also the optimal factors show an increase from the life span of 50 years to 100 years. The optimal values for life span of 100 years are higher than the ones for 50 years life span which show that the use of long range life spans are preferable to the medium range spans. The relative difference between the optimal values shows that application of the isolation system has weak justification for short design life spans.

Table 3.The obtained design parameters with residential occupancy and discount rate of 0%

T_D (y)	I_{opt}		V_{opt}		$(V_{opt,Is} - V_{opt,Fx}) / \lvert V_{opt,Fx} \rvert$
	Fx	Is	Fx	Is	
2	0.70	I_{min}	0.24	0.07	−0.70
100	1.06	0.64	4.49	4.45	−0.01

The values obtained with four discount rates of 1% to4% aregiven in Table4. For the fixed system, it is seen that the optimal importance factors gradually decrease as the discount rate increases.As the life cycle costs are more discounted with increase ofλ, the difference between the benefit and the time-distributed cost grows. As a result, the lower optimal factorsare enough to provide balance between rates of the value curve and the curve related to the normalized structural cost (Figure 2). Also, the optimal values increase due to growthin difference between benefit and cost. Moreover, the relative difference values decrease with increase in discount factor.

Table 4.The obtained design parameters with residential occupancy and life span of 50 years

λ (%/y)	I_{opt}		V_{opt}		$(V_{opt, Is} - V_{opt, Fx}) / \| V_{opt, Fx} \|$
	Fx	Is	Fx	Is	
1	0.95	0.54	4.32	4.05	−0.06
2	0.92	0.51	4.48	4.17	−0.07
3	0.90	0.48	4.59	4.26	− 0.07
4	0.88	0.46	4.68	4.33	− 0.07

The obtained results demonstrate the capability of the proposed framework for value-based design of fixed and isolated structures under different design conditions. In addition, by the framework the selection on the type of structural system can be justified based on the value concept.

CONCLUSIONS

In the present study, the optimal design of the seismically isolated structures is discussed from the value-based viewpoint. The most influential variables associated with the optimal performance of the structures were recognized as the occupancy type, design life span and the discount rate. A value-based design framework based on the cost-benefit analysis was proposed in which the three mentioned variables are introduced. A four-story building structure of five different structural configurations is designed according to UBC 97 with low to very highimportance factors with and without base isolation. For cost-benefit analysis of both fixed and isolated structures, two occupancy types of residential and hospital were selected to represent respectively the ordinary and special applications. Also, three life spans of 2, 50 and 100 years are considered respectively as short, medium and long term operational durations, as well as four discount rates of 1%, 2%, 3% and 4% were selected to represent economical environments with slow to rapid growths.

From the results obtained through the parametric study, it was shown that in the case of the residential occupancy, applying the isolation system does not result in improvement in the value for the owner despite that the isolated structures provide much higher performance compared to the fixed ones. In contrast, the use of isolation system provides improvement in value in the case of hospital occupancy. In addition, it was found that the isolated superstructures with optimal performance have lower weight and consequently lower construction cost than the corresponding ones with fixed base for both occupancies. For the residential occupancy, the obtained optimal importance factors are lower than the ones for the hospital occupancies; however in UBC 97, a fixed importance factor is recommended for all occupancies. By comparing the results for different life periods it was found that the useof long life spans provides more improvement in value than the one with medium spans.

The results obtained from different percentages of the discount rate suggest that applying the isolation system in developed economies with low discount rate is more justifiable than in developing economies with high rates. Also, the results showed that as the discount rate increases, the optimal importance factorlies on the lower ranges. The results of this study confirm that the structural design problem is not only related to the structural performance but also to the variables such as design life, occupancy type and economic environment of the society. Additionally the results demonstrated the capability of the proposed framework to be efficiently applied in optimal design problems.

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