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Research Paper

A Cost-Value Approach for Design of Base-Isolated Structures

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ABSTRACT

In this work, a value-based design approach is used to rationalize the structural design procedure in terms of initial investment and structural performance as well as other related parameters like design life span and economic conditions of the region. In this approach, at first, a definition for design value is introduced in which the structural performance is converted to cost equivalent, and based on this definition a value design curve for the structural system is found. Then, an optimality criterion is adapted to find a rational design point for the structural system. The results of such studies for residential occupancy shows the fact that a sub-optimal value design point for a base-isolated structural system requires much lower design shear force than the one usually recommended by code-based design approaches. According to the results, the base isolation system does not provide a strong justification to be used instead of the fixed-base system even in economies with high discount rates.

Keywords:
Value analysis;
Cost-benefit analysis;
Rate-based design;
Value-based design;
Base isolation

1. Introduction

The concept of seismic design approaches in last two decades has evolved from the life safety approach to performance-based design methodologies [1]. In this approach the designer is capable of defining a certain level of structural performance by the means of predefined limitations on structural deformation or forces. Recently, a more tangible version of this approach is developed in which structural performances is translated into the monetary equivalent of earthquake inflicted damages on the building. This is considered as a basis for development of the next generation of seismic design procedures [2-3]. The main requirement for this approach is the ability to estimate long-term earthquake damages on a structural system [4]. However, having an estimation on the level of the earthquake damage cost for a building, it is still a challenge to find the desired level of structural design performance for the system. Such a decision-making procedure should be based on a rational balance among the monetary values of earthquake damage cost, initial investment on the building and its expected long-term operational benefits.

Cost-benefit analysis is a practical tool for value assessment in structural design process. In recent years, various frameworks have been proposed to find the optimal structural design performance for a building, using cost or cost-benefit analyses [5-10]. Most of these studies have been focused on the cost analysis alone [5-6, 9-10]. Moreover, in most of these studies, important parameters such as design life span, occupancy type and economic conditions of the region in which the project is intended to be constructed have not been taken into consideration.

Application of value assessment is even more important in design process of base-isolated structural systems due to the higher initial investment in these systems. By applying cost-benefit analysis on a base-isolated structural system, a level of structural performance for the building can be provided that comes in balance with initial investment. However, this is in contrast to the code-based design regulations (e.g., [11-12]) for such buildings, because the design codes usually require a high level of structural performance for the isolated systems. So far, a quite limited number of investigations on cost-benefit analysis of base-isolated structural systems have been reported (e.g., [13-15]).

The first aim in this work is to introduce a value-based approach in design of building structures and the second one is to study whether the use of isolation system is justifiable for structures with residential occupancy in different conditions. To do this, a value measure is defined to incorporate all the important cost-benefit factors into a single decision-making parameter. In the evaluation of the earthquake damage cost, a cumulative approach is proposed by which contribution of all earthquake intensity levels (from weak to severe) is incorporated. Having the value measure, a simple algorithm is adopted to find a sub-optimal design performance for the building. Using this algorithm, the optimal design solution in case of base-isolated buildings with different design life spans and economic conditions is studied. Besides, the identical buildings with fixed-base system are also studied in the present work. In contrary to previous works, the present work by applying an explicit approach aims to clearly show the effects of most important parameters in design of base-isolated structures from the value-based point of view.

2. Value Assessment

A value-based design approach is practically based on providing a rational proportionality between the benefit and the cost of the project. This proportionality is the value itself and comes in the form of a decision-making parameter in the design procedure. This approach needs cost-benefit analysis on all the influential parameters in such studies. These parameters are the expected cost of earthquake inflicted damages on the building, maintenance and operational cost and the initial cost for construction of the system.

2.1. Value Definition

Value-based design framework requires a definition for the value in which all the above-mentioned parameters are taken into account. In this work, the value is defined as a decision-making index in the form of a ratio based on the monetary value of the net benefit to that of the construction cost. This measure is defined as follows:

$$V = \frac{R - C}{C_I} \tag{1}$$

in which V is the value measure and R represents the total benefit from renting the building in its life span. In this definition, C_I is the construction cost and C is the total cost of the building during its life span. All these monetary values (R, C, C_I) have to be scaled to their equivalents at the time of construction. In this definition, the value measure above the unity represents a case in which the investment on the project is justifiable.

3. Value Component Assessment

In assessment of value components, except for the construction cost (C_I), the components are considered as the time-dependent monetary entities. Among them, estimation on the earthquake damage cost is quite complicated because of its dependency on the seismicity of the region, structural responses, damage-intensity relationship and the cumulative nature of damage estimation for a building subjected to earthquake hazard.

3.1. Construction Cost

The construction cost is the sum of various costs and expenses related to the material, labor, machinery, management and the overhead. For estimating the construction cost various methods based on regression models, neural networks and case-based reasoning models have been proposed [16-18]. This cost is usually divided into structural and non-structural costs based on available databases in terms of occupancy type of the building (e.g., [19-20]).

3.2. Life Span Costs

The cost of building during its design life span consists of the followings:

$$C = C_{OM} + C_{ER} \tag{2}$$

wherein C_{OM} is the operation and maintenance cost and C_{ER} is the cost of earthquake damages during the building life span. The other cost items like demolition of the building at the end of its life or renovation costs may also be taken into account.

3.2.1. Operational Cost

Operational cost includes maintenance, repair and replacement of its non-structural and structural elements during the building operation. In addition, the cost of utilities and taxes should also be taken into account. If this cost is assumed to be uniformly distributed over the design life span, it can be expressed as follows [5]:

$$C_{OM} = C_0 \times \frac{(1 - e^{-\lambda T_D})}{\lambda} \tag{3}$$

in which, C_0 is the annual operating cost at the time of construction, T_D is the design life span and λ is the annual discount rate. Discount on the future costs is necessary to scale time-distributed costs to their equivalents at the time of construction. In the absence of inflation, discount rate can be considered equal to the rate of return on investment; otherwise, discount rate is the rate of return on investment minus the inflation rate [21]. In this approach, economy is considered stable and discount rate is assumed constant over time.

3.2.2. Earthquake Damage Cost, A Cumulative Approach

Structures in their life span are subjected to a variety of earthquake hazard intensities. While, small earthquakes have higher rate of occurrence with less capability to cause damage, large earthquakes are capable of causing serious damages on the building with less probability of occurrence. To quantify the total earthquake damage costs, all of these damages should be taken into account by integrating them over all earthquake intensity levels. In this integration, the probabilistic nature of earthquake events should be taken into account. Using Poisson distribution, the probability of occurrence of earthquakes with average return periods greater than T_R (in an arbitrary time period of *t*) is expressed as follows [22]:

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

Earthquake intensities in this integration are also required to be defined explicitly. In this work, earthquake intensity levels are classified based on their average return periods T_R. In a typical code-based design approach, the return period of design earthquake is recommended to be equivalent to $T_R = 475$ years. In this case, the earthquake intensity at this return period is defined by a specified response spectrum (S_{475}).

To estimate earthquake intensities at other return periods, the following relationship is used to scale the spectrum corresponding to the return period of 475 years to the one with return period of T_R.

$$\frac{S_{T_R}}{S_{475}} = b \times \log(1 + a \times T_R) \tag{5}$$

where S_{T_R} is the scaled spectrum corresponding to the return period of T_R and *a* and *b* are constants.

Figure (1) illustrates a schematic representation for damage-intensity costs in terms of earthquake return periods. Damage-intensity curve in this figure is dependent on the structural performance and occupancy type of the building. Having such a damage-intensity curve for a typical structure, a probabilistic model based on Equation (4) can be used to evaluate the expected damage for the

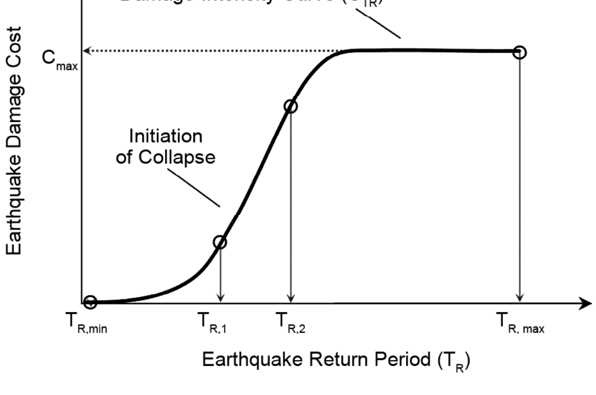

Figure 1. A typical damage-intensity curve.

building during its life span by integrating earthquake expected damages at all intensity levels.

Damage-intensity curve, CTR, incorporates the contribution of all types of earthquake damages on the building at each earthquake intensity considering structural and non-structural damages including injury, fatality, out of service and so on. To estimate the extent of damage on the system at a given intensity, various methods using analytical and numerical approaches (e.g., incremental dynamic analysis), expert opinions, method of reasoning and experimental studies can be used. The full damage cost in this curve, $C_{\max}$, is corresponding to the damage cost of the building in case of complete collapse of the structure.

Having damage-intensity curve and the probability distribution of earthquake events, the expected cost of earthquake damage can be obtained using a cumulative approach that integrates damage costs from all the probable earthquake intensities over the design life span of the building.

$$C_{ER} = \frac{1}{T_L}\int_0^{T_L} e^{-\lambda t}\, dt \times \int_{T_{R,\min}}^{T_{R,\max}} -C_{TR}\, d\,[1-e^{-\frac{t}{T_R}}] \quad (6)$$

where C_{ER} is the cumulative expected damage cost corresponding to the earthquake return periods between $T_{R,\min}$ and $T_{R,\max}$ for the structure over its design life span (T_L) and d [.] is the differential operator with respect to T_R. $T_{R,\min}$ is assumed as the return period corresponding to the minimum earthquake intensity level (capable of inflicting damage on the building) and $T_{R,\max}$ is the return period corresponding to the maximum level of intensity for earthquakes in the region.

In Equation (6), the first integral term scales the expected earthquake damage cost to the time of construction assuming a uniform distribution of events during the life span of the building. In the second integral term, the differential operator is applied to obtain the probability of the occurrence of damage cost corresponding to the return period of T_R. Applying the differential operator and simplifying the algebraic expressions, the expected damage cost is formulated as:

$$C_{ER} = \frac{1}{\lambda}(1-e^{-\lambda T_L}) \times \int_{T_{R,\min}}^{T_{R,\max}} \frac{C_{TR}}{T_R^2}\, e^{-\frac{T_L}{T_R}}\, dT_R \quad (7)$$

Due to the probabilistic nature of the expected damage, C_{ER} is usually less than $C_{\max}$ in damage-intensity curve as shown in Figure (2). In this figure, each point on the cumulative expected damage curve is obtained independently by changing the upper limit of the integral from $T_{R,\max}$ to T_R of that point.

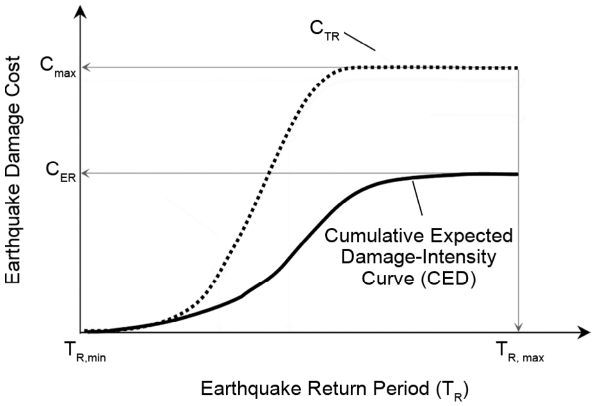

Figure 2. Cumulative expected damage and damage-intensity curves.

3.2.2.1. Earthquake Cost Break Down

For usual buildings, interstory drift and floor acceleration are considered as the main cause of damage infliction on the structure. In this case, the earthquake damage costs can be broken down as:

$$C_{TR} = \overset{\mathit{\Delta}}{C}_{TR} + \overset{A}{C}_{TR} \quad (8)$$

in which $\overset{\mathit{\Delta}}{C}_{TR}$ and $\overset{A}{C}_{TR}$ stand for damage cost due to drift and acceleration, respectively. While damage costs for non-structural elements and the building contents are a function of drift and acceleration, the other costs are a function of drift alone.

$$\begin{aligned} C_{TR} = {} & \overset{\mathit{\Delta}}{C}_{TR,SR} + \overset{\mathit{\Delta}}{C}_{TR,NR} + \overset{A}{C}_{TR,NR} + \overset{\mathit{\Delta}}{C}_{TR,CT} + \\ & \overset{A}{C}_{TR,CT} + \overset{\mathit{\Delta}}{C}_{TR,IN} + \overset{\mathit{\Delta}}{C}_{TR,FA} + \overset{\mathit{\Delta}}{C}_{TR,RE} + \overset{\mathit{\Delta}}{C}_{TR,DT} \end{aligned} \quad (9)$$

where $\overset{\mathit{\Delta}}{C}_{TR,SR}$ is the damage cost for structural elements, $(\overset{\mathit{\Delta}}{C}_{TR,NR} + \overset{A}{C}_{TR,NR})$ is the same cost for non-structural elements and $(\overset{\mathit{\Delta}}{C}_{TR,CT} + \overset{A}{C}_{TR,CT})$ is the same for the building contents. Moreover, $\overset{\mathit{\Delta}}{C}_{TR,IN}$ is the cost of injury, $\overset{\mathit{\Delta}}{C}_{TR,FA}$ is the fatality cost and $\overset{\mathit{\Delta}}{C}_{TR,RE}$ is the cost of relocation during an earthquake. In Equation (9), $\overset{\mathit{\Delta}}{C}_{TR,DT}$ is the earthquake damage cost due to out-of-service intervals.

3.3. Benefit

The benefit of a building is considered equivalent to its rental income during its design life span.

$$R = R_L - R_S \tag{10}$$

where R_L is the net rental income and R_S is the loss of income during the out of service intervals. Assuming the rental increase rate to be equivalent to the inflation rate, R_L is calculated as below:

$$R_L = R_0 T_L \tag{11}$$

in which R_0 is the net annual rent of the building at the beginning of its life span.

3.4. Out of Service Loss

By estimating the out of service intervals for each earthquake intensity level, a downtime curve similar to the one shown in Figure (1) can be obtained. Using this curve, the out of service loss estimation can be handled similar to the procedure used for estimating C_{TR}.

$$R_S = R_0 T_L \int_{T_{R,\min}}^{T_{R,\max}} \frac{T_{TR}}{T_R^2} e^{-T_L/T_R} \, dT_R \tag{12}$$

In this relationship, T_{TR} is downtime curve in terms of earthquake return period. Having all the cost and benefit components estimated from the above procedures, the value parameter can be determined.

4. Rate-Based Design Approach

Value-based design approach in this study is a decision-making algorithm based on the value definition represented by Equation (1). All the required data to evaluate the so-called "value curve" based on this definition can be directly picked up from the results of cost-benefit analyses. A schematic representation for the value curve is illustrated in Figure (3).

According to this figure, if the structural performance increases, the value measure improves. On the other hand, this trend needs more investment on the lateral load resisting mechanism of the building C_S. In the figure, C_S is normalized with respect to a nominal cost for lateral load resisting capacity of the building C_S^*. In this work C_S^* is considered equivalent to the minimal cost for the lateral load resisting capacity for the structure.

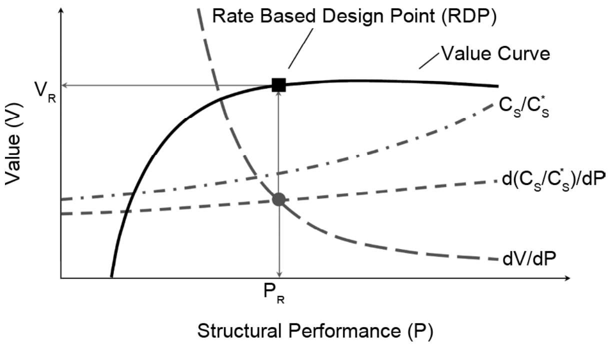

Figure 3. Value curve and the rate-based design point definition.

To pick a design point, a decision-making algorithm based on an optimality criterion for value design point should be applied. In the present work, a rate-based decision-making policy for determination of a suboptimal design point for the structural system is adopted. This policy is based on the equivalency of the rate of change in the value measure and in the structural costs (shown in Figure 3). These rates of changes are shown in the same figure (dV/dP and $d(C_S/C_S^*)/dP$). Equality of these two rates (at their intersection point) provides us with the rate-based value design point (R_{DP}) and its corresponding structural performance demand (P_R). Additional investment on the structural system beyond this point (choosing $P > P_R$). results in a lower return rate on the value of the structural system.

The value corresponding to P_R is considered as the rate-based value design point (i.e., V_R). Determination of structural design point P_R (corresponding to V_R) in this study, is different from the methods in which the structural design point is derived by the optimality criteria based on the minimization of cost or maximization of the difference between benefit and cost (as reported by [7]).

5. Case Studies

In the current work, the effects of the design life span and the discount rate on the value design curve and the value design point are examined through the case study of a building with two classes of structural system (fixed-base and base-isolated).

5.1. Structural Modeling

A four-story structural system in five different configurations (from a low level of strength capacity to the high one) is chosen for the study. These structures are designed as ordinary type of braced frame systems. In case of base isolation, the same structural systems are used as super-structures located on top of the isolated layer. These structures are 16 by 16 m in plan, including four bays each at the length of 4.0 m with the story height of 3.3 m. Two braced frames in each direction resist the lateral forces on the building. For simplicity, equivalent two-dimensional models for these structures are used in the analyses. All the analyses have been carried out in OpenSees environment [23]. Figure (4) shows these models.

In the model, beam connections are linear elements with rotational stiffness equal to 10% of the flexural stiffness of the beams (Figure 5). With the assumption of lumped plasticity, all the braces are modeled using elastic elements along with axial elasto-plastic zero-length links at their ends. Accordingly, all the plastic deformations in the structural system are arranged to be concentrated at braces.

The behavior of the braces under tension and compression actions are independently modeled using two parallel tension and compression link elements. An elastic perfectly-plastic behavior with the ability of modeling elongation of braces (by accumulation of damage in tension) is assigned to the tension links. The compression link is modeled to resist actions up to the buckling load, following by a drop in its load carrying capacity to 20% as compression continues. With this model, the structural model is capable of representing the pinching effects of braces in the system. The compound hysteretic behavior of the brace is shown in Figure (6).

In case of base-isolated structures, the isolators

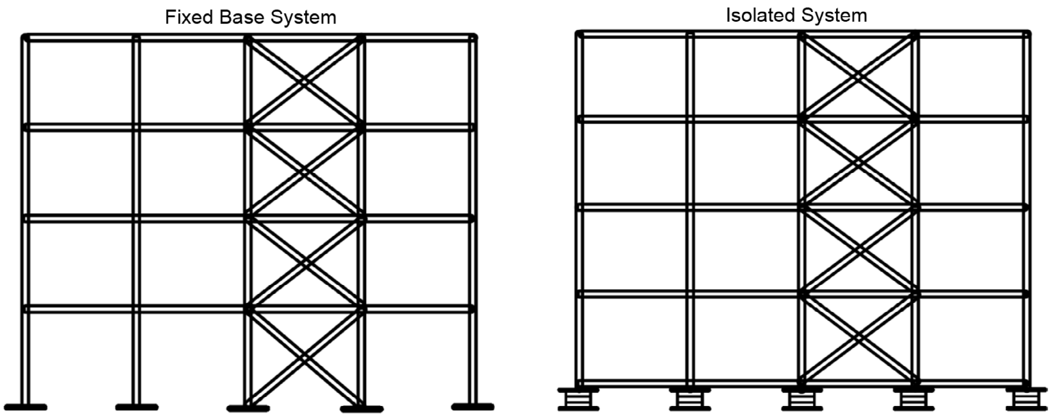

Figure 4. Two-dimensional models for fixed and isolated structures.

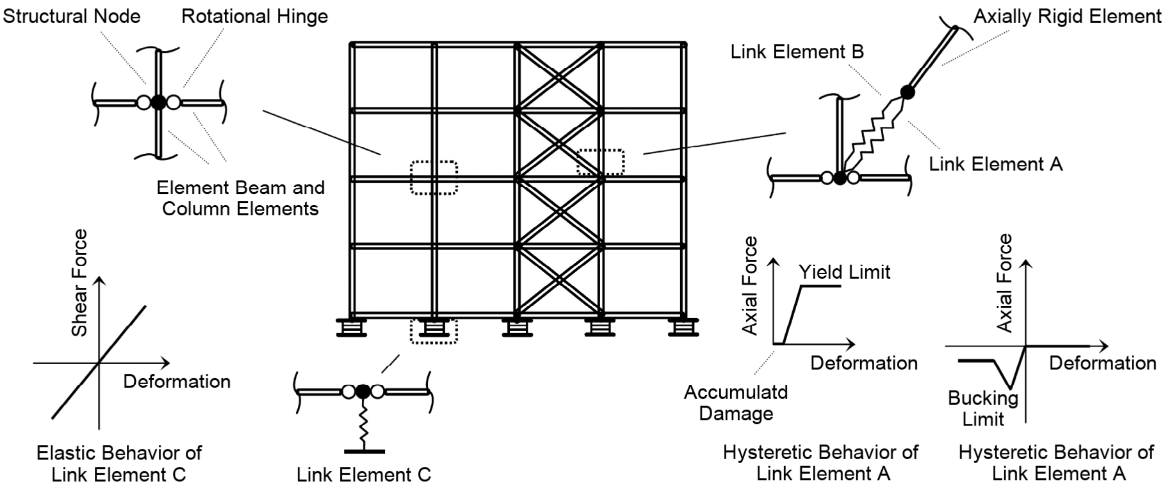

Figure 5. Behavior of structural elements used in modeling.

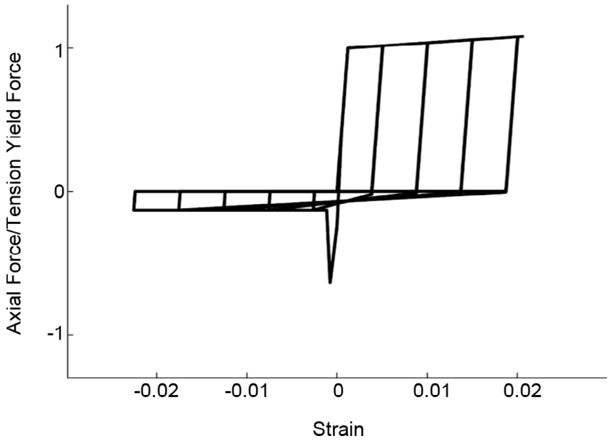

Figure 6. Compound hysteretic behavior of a single brace.

are modeled by linear elastic link elements. The shear stiffness of the link elements are assigned such that the isolation period of a rigid superstructure equals 2.2 s.

The fixed-base structures are designed according to Uniform Building Code 97 using the static force procedure. The structure labelled as S3 is designed for soil type C and peak ground acceleration of 0.40 g with importance factor (I) of unity. Besides S3, four other structures are designed with the ratio of their base shear force to that used for the design of S3. This ratio is denoted by *P* as the structural performance parameter. The structures from S1 up to S5 with their base shear ratios are tabulated in Table (1).

While the S1 configuration has a low strength capacity, the S2 configuration cannot still meet the minimum required strength for a typical building according to the building code. The structure S3 is designed based on the building code requirements for standard occupancies such as typical residential buildings. The structure S4 satisfies code requirements for special buildings such as hospitals. The S5 configuration is designed with the higher strength than those recommended by the building code.

The structural weights for these configurations and the weights of the lateral load resisting mechanism of these structures (braces and their neighbouring columns) are all tabulated in Table (1). Using modal analyses, the first natural period of these structures in both fixed and isolated configurations are given in the same table.

5.2. Cost-Benefit Analysis

Occupancy type of a building is considered as one of the influential parameters in cost-benefit analysis of a structural system. In defining occupancy, factors such as value of non-structural elements and contents, density of occupants and business interruption losses are important. In this study, the parameters needed to quantify these factors are chosen based on the data reported elsewhere [24]. Some of these parameters are tabulated in Table (2). The out of service cost for the residential building is assumed zero because the loss of rental income is subtracted from the benefit (Equation 10).

The construction cost for a typical residential occupancy is based on the data provided for design life span of 50 years [20] that is tabulated in Table (3). In this table, C_0 and R_0 are the annual operational cost and rental income of the building, respectively. All the costs and benefits in

Table 1. Structural properties of the selected configurations.

Structural Configuration	P	Structural Weight (kN)		1st Natural Period (s)	
		Total	Lateral Load Resisting	Fixed	Isolated
S1	0.4	343	93	0.88	2.28
S2	0.7	380	131	0.73	2.24
S3	1.0	420	170	0.63	2.22
S4	1.3	449	200	0.58	2.21
S5	1.6	496	248	0.52	2.20

Table 2. Influential parameters in defining occupancy.

Occupancy Parameter	Ratio of Non-Structural Value to Construction Cost	Ratio of Contents Value to Construction Cost	Presence of Occupants		Out of Service Cost
	–	–	Persons per 100 m^2	Hours per Day	USD/m^2/year
Parameter Value	0.80	0.2	3	14	0

Table 3. Cost-benefit parameters in terms of occupancy.

Occupancy	Construction Cost	Value of Human Life	C_0	B_0
	USD/m^2	USD/person	USD/m^2/year	USD/m^2/year
Residential	1,000	1,000,000	12	96

Table 4. Constructional cost breakdown in the studied configurations.

Structural Configuration	C_S (10^5 USD)		C_{SR} (10^5 USD)		C_I (10^5 USD)	
	Fixed	Isolated	Fixed	Isolated	Fixed	Isolated
S1	0.27	0.81	2.06	2.60	10.25	10.79
S2	0.33	0.95	2.12	2.74	10.32	10.93
S3	0.44	1.20	2.23	3.00	10.42	11.19
S4	0.56	1.56	2.36	3.35	10.55	11.55
S5	0.69	2.00	2.48	3.79	10.68	11.98

Tables (2) and (3) are evaluated based on 1997 values. The study of hospital occupancy as an important occupancy type is carried out in a separate work by the authors [25].

In addition to the typical 50 years life span for the buildings, the life spans of 2 and 100 years are also studied in this work. Moreover, the effects of economic conditions of the region are taken into account by choosing the three discount rates in calculation of life span costs (λ = 0, 1 and 2% to represent economies with different growth rates).

5.2.1. Evaluation of Construction Costs

The construction costs of S1 to S5 building configurations for both fixed-base and isolated structural systems are given in Table (4). In this table, C_S is the construction cost of the lateral load resisting mechanism of the building (in case of isolated structure accompanied by the isolation cost). For the structural configurations S4 and S5, the C_S cost is relatively large because of their heavier structural members (including foundations) and also the larger displacement demands for the isolation layer. C_{SR} in this table represents the total costs of the structural system (including both gravitational and lateral load resisting members). The total cost of the building (C_I in Table 4) is much higher than the cost of the structural parts due to the dominance of the non-structural elements in total cost of the building.

The cost of non-structural elements for the life spans of 2 and 100 years are estimated 50% and 150% of that for the life span of 50 years, respectively.

5.2.2. Damage Estimation

Damage estimation in this study is based on the incremental dynamic analyses to find the so-called damage-intensity curve discussed earlier in this work. Altogether, 15 earthquake return periods are used for the analyses (from 9 to 9975 years to have adequate curve fit). The return periods of 9 and 9975 years are considered $T_{R,min}$ and $T_{R,max}$, respectively. In the analyses, seven California earthquake records for Soil type C without near field characteristics are selected from PEER Strong Motion Database [26]. Then, the selected records are scaled to each of the 15 levels of earthquake intensities. The scaling approach is based on the spectrum matching technique using the design spectrum recommended by UBC 97 code [11]. Scaling of the earthquakes for different intensity levels is based on using Equation (5) with $a = 0.577\times10^{-2}$ and $b = 1.746$ calculated based on data provided in [27] for California zone. A total number of 525 nonlinear time-integration analyses for each group of fixed and isolated structural configurations have been performed. In each analysis, maximum interstory drifts and floor accelerations are evaluated. Then, the maximum drifts and accelerations are used in determination of damage costs for each earthquake intensity level. The damage cost for each earthquake intensity level is taken as the median between damage costs resulted from the seven earthquake records.

Damage cost for the building is calculated in each story separately using a set of predefined damage functions. Each function is in terms of drift or acceleration and varies between two limits of performance measures. The lower limit corresponds to the no damage infliction to the story and the higher limit describes the situation in which a complete damage to the story would be expected (equivalent to story collapse). In the interval between these two limits, the damage cost varies by a power function with the exponent of *r*.

For damage functions related to drift, the lower and higher limits are assumed to be 0.4% and 4%, respectively. For damage functions related to the acceleration, these limits are taken 0.5 g and 2.0 g. In estimation of the total damage, if one of the stories reaches to its collapse drift, it is assumed that the damage extends to the whole building (collapse of the building). The damage is also considered complete, if one of the columns reaches its buckling load. To determine the values of exponent r in any damage type (injuries and fatalities for example), the damage dataset provided elsewhere is used [24].

Having all these, damage-intensity curve, C_{TR}, was developed using interpolation techniques across the earthquake damage costs for the selected earthquake return periods. Figure (7) shows an example of such curve for the residential occupancy in all structural configurations. According to the figure, as the strength capacity increases, damage built up moves toward higher earthquake return periods. In addition, the figure also shows that the damage built up in the isolated system starts in much higher earthquake return periods.

In Figure (8), the cumulative expected damage curves (CED) for the residential occupancy with the design life span of 50 years and zero discount rate are shown. According to this figure, the capability of the isolation system in reducing the expected damage on the buildings is phenomenal. The figure also shows that the CED curves have a jump in their damage costs at the return period in which collapse in the building initiates (shown in Figure 7).

In Table (5), the expected earthquake damage costs (at $T_{R,max}$ = 9975 years) are shown for all structural configurations. According to this table, the expected earthquake damage cost rapidly decreases with the increase in structural strength for both fixed and isolated systems.

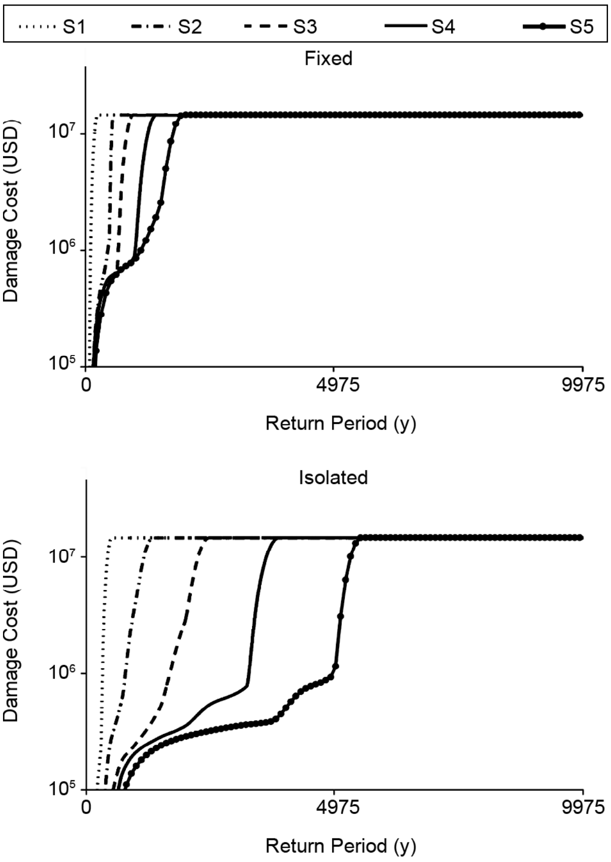

Figure 7. Damage-intensity curves for structural configurations.

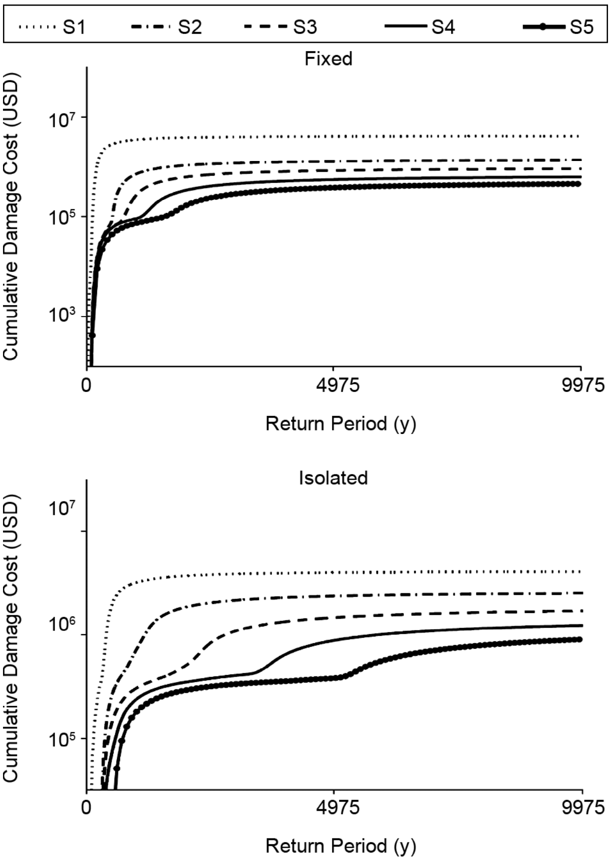

Figure 8. Cumulative expected damage curves for structural configurations.

Table 5. Expected damage costs in terms of structural configurations.

Structure	C_{ER} (10^5 USD)	
	Fixed	Isolated
S1	41.3	16.7
S2	13.6	6.3
S3	9.2	2.9
S4	6.3	1.5
S5	4.6	0.8

5.2.3. Benefit Evaluation

The life span benefits for the residential occupancy (assuming zero discount rate) are shown in Table (6). These values show no significant variation in terms of structural types or strength (S1 to S5). The small differences in benefit evaluations are due to the change in their downtime intervals.

Table 6. Benefits evaluation in terms of structural configurations.

Structure	R (10^5 USD)	
	Fixed	Isolated
S1	48.9	49.0
S2	49.0	49.1
S3	49.1	49.1
S4	49.1	49.1
S5	49.1	49.1

All the contributing parameters in cost-benefit design framework (CI, CER and R) can now be represented in terms of structural configurations, S1 to S5, using regression analyses. Figure (9) illustrates such relationships for the case of residential occupancy, assuming 50 years of life span and zero discount rate. In this figure, the structural configurations are represented by their corresponding base shear ratios, P, given in Table (1).

These curves are needed in determination of the value curve to find the suitable design point for the system in terms of structural performance parameter (i.e., the base shear ratio).

5.3. Rate-Based Design Solution

Figure (10) presents value curves and the rate-based design points (marked with bullet signs) for the residential occupancy with different design life spans and discount rates. In determination of the rate-based design points, C_S^* is considered equivalent to the minimal cost for the lateral load

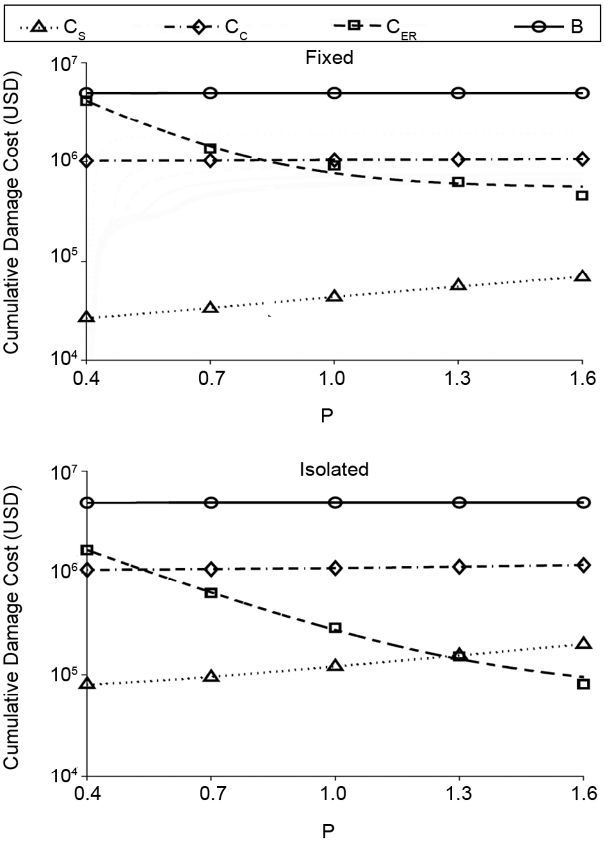

Figure 9. Regression curves for discrete cost and benefit components.

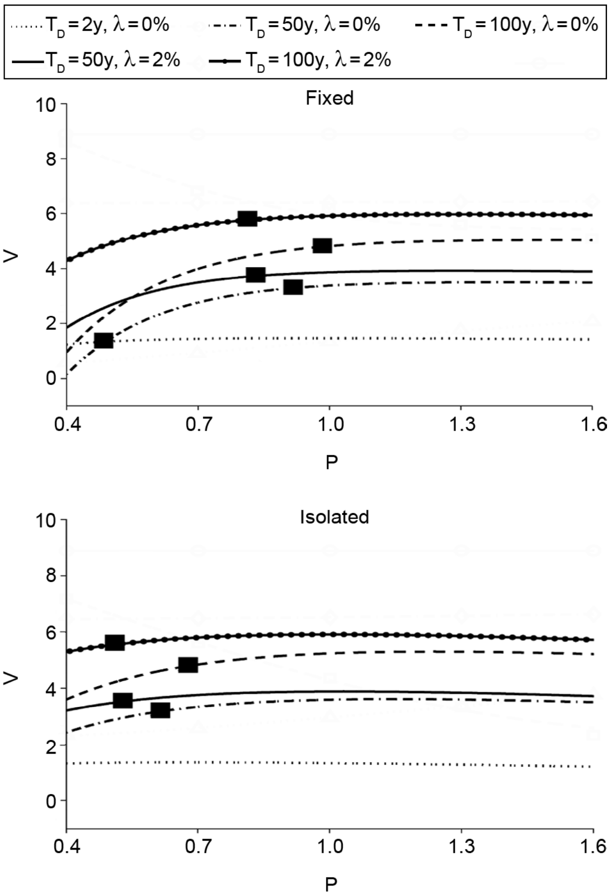

Figure 10. Value curves and rate-based design points in terms of design life span and discount rate.

resisting capacity of the structure ($C_S^* = 0.26\times105$ USD for a structure designed with $P_{min} = 0.25$).

As shown in the figure, the rate-based ratios (i.e., P_R) for the isolated structures are typically much lower than the ones for the fixed-base systems. It should be noted that, the resulted P_Rs for the isolated system does not necessarily provide a high level of structural performance. This is in contrast with the high level of structural performance usually required for base-isolated structural systems in code-based design approaches (e.g., UBC97 [11]). The value-based design parameters for the residential occupancy are tabulated in Table (7). According to the table, the application of base isolation does not have a strong justification for residential occupancy when its lower V_R is compared with the one for the fixed-base system (3.29 vs. 3.17).

The design base shear resulted from the value-based approach and the ones recommended by UBC 97 for the same structural systems are given in Table (8). For the fixed-base system, the results from the value-based method are slightly lower than the ones recommended by the UBC 97 code. For the base-isolated system, the difference in design base shear between the value-based and code-based methods is 66%. The main reason for this difference is due to the fact that the aim in the code procedure is to provide a high level of structural performance for the system. Hence in the code procedure, the same importance factor is used for all occupancy types (e.g., [11-12]). Consequently, structures with residential occupancy are designed with base shear force the same as the one used for special occupancies such as hospitals.

In Figure (10), the value curves for the design life spans of 2 and 100 years are shown and their corresponding rate-based design parameters are tabulated in Table (9). According to Tables (7) and (9), the PRs for the life span of two years are much lower than the ones for the life span of 50 years (about 40% lower). In this case, the rental income for the building with temporary usage (two-year life span) is assumed five times of the income rate of the building with 50 years of life span. This assumption is based on the expert opinion on the cost of temporary housing in remote areas. According to this table, PRs for base-isolated structural system for temporary housing is quite low (i.e., $P_R = 0.26$). The table also shows that the P_Rs for design life span of 100 years are slightly higher than those for 50 years design life span.

Comparing Tables (7) and (9), the V_Rs for the life span of 100 years in residential buildings are higher than the ones for 50 years design life span. The reason for this jump in value is the fact that the construction cost is not actually doubled if it compares with its life span (the rise in the construction cost is 150%).

In the economies with high-growth rates, the time-distributed costs are subjected to high discount rates. As shown in Figure (10), applying the higher discount rates causes the value curve to shift toward the lower range of the base shear ratio. The value-based parameters for the discount rates of 1% and 2% are given in Table (10). For both fixed and isolated structural systems, the P_Rs decrease by the increase in the discount rate.

Table 7. Value-based design parameters for design life span of 50 years and zero discount rate.

Value-Based Design Parameters					
V_R		P_R		$C_{S,R}$ (10^5 USD)	
Fixed	Isolated	Fixed	Isolated	Fixed	Isolated
3.29	3.17	0.92	0.61	0.41	0.90

Table 8. Design base shear obtained by using value-based design approach and UBC 97 code.

Value-Based Design Base Shear (Kn)			
Value-Based Design		UBC 97	
Fixed	Isolated	Fixed	Isolated
2085	1382	2266	2291

Table 9. Value-based design parameters for design life spans of 2 and 100 years with zero discount rate.

T_L (y)	V_R		P_R		$C_{S,R}$ (10^5 USD)	
	Fixed	Isolated	Fixed	Isolated	Fixed	Isolated
2	1.33	1.25	0.48	0.26	0.28	0.76
100	4.80	4.79	0.98	0.68	0.43	0.94

Table 10. Value-based design parameters in terms of discount rates with design life span of 50 years.

λ (%)	V_R		P_R		$C_{S,R}$ (10^5 USD)	
	Fixed	Isolated	Fixed	Isolated	Fixed	Isolated
1	3.54	3.37	0.87	0.57	0.39	0.88
2	3.73	3.53	0.83	0.53	0.38	0.86

This is due to the fact that in economies with higher discount rate (i.e., developing countries), scaling all the time dependent costs of the structure to the inauguration time of the building makes this cost lower if it is compared to the economies with lower discount rate (see Equation 7).

According to Tables (7) and (10), the justifiability of using the base isolation system does not change with increase of the discount rate, since the difference between the V_Rs of the fixed-base and base-isolated systems do not show a significant variation.

6. Conclusion

In this study, a value-based design framework is introduced to provide the structural engineers with a rational choice in design of structural systems subjected to earthquake loads. This framework is based on a definition for value as a decision-making measure in the design procedure. This measure is in terms of monetary values of all the design parameters in a structural system and comes in the form of a non-dimensional scalar. Estimation on the value in terms of change in structural performance level for a building subjected to earthquake loads provides the designer with the ability to find optimal performance for the structural system. This procedure is, in fact, a cost-benefit analysis practice that is simplified by a new optimality criterion to find a sub-optimal value design point for the system.

To show the ability of this framework in design procedure of base-isolated buildings, a four-story structural system with residential occupancy and in separate configurations (fixed-base and base-isolated) is chosen for the study. The fixed-base structure is designed based on UBC 97 design code in five different levels of lateral strength (from very low to very high levels) to represent the change in structural performance. The same structural configurations are equipped with the base isolators and the resulted 10 structural systems are used in the value-based design framework to find the sub-optimal structural performance for both fixed-base and isolated structural systems. In the cost-benefit analysis, the three different life spans for the buildings (2, 50 and 100 years) along with the three separate economic conditions for the project (represented by discount rates of 0%, 1% and 2%) are chosen as the main design parameters for these structures.

In an extensive parametric study, the outcome of the above design procedure indicates the followings:

1) According to the assumptions and the dataset used in this work, the base-isolated buildings with residential occupancy can be designed with the lower base shear force (about 40%) than the ones recommended by the typical design codes. For the fixed-base residential buildings, reduction in structural demands is marginal.
2) The use of base isolation for residential buildings is found not to have a strong justification according to this design approach even in the economies with high discount rates.
3) According to the results of this study, designing of buildings with higher life span is usually recommended because of their high values comparing with the shorter life span ones.

By the proposed methodology, the optimal design point in case of other structural systems or building occupancies can be further studied.

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