Performance based design using life cycle cost analysis

M. Seçer, Ö. Bozdağ
Dokuz Eylul University, Izmir, Turkey

ABSTRACT: Life cycle cost analyses is one of the useful tool for evaluating the lifespan performance of buildings. The sum of initial and future costs associated with the construction and operation of a building over a period of life time is determined by life cycle cost analysis. In this study, a moment-resisting steel building is designed using various base shear values and the life cycle cost of each design is determined for different earthquake intensities. Static pushover analysis is used to calculate yield base shear value of each design and initial costs, the cost of the expected damages caused by earthquakes that are expected to occur during the design life of the buildings are estimated. The optimum economic design of the steel building is determined by using yield base shear and total cost values.

1 INTRODUCTIONS

Kocaeli and Düzce Earthquakes (1999) in Turkey caused significant damage to buildings, public facilities, infrastructures and many casualties. In these catastrophic earthquakes, number of loses in terms of human lives and economic loses were too high. There were 18,373 accounted deaths and 48,901 injuries (Erdik, 2000). If it is assumed that the indirect social economic loses should be about as much as the direct physical loses, the total economic lost were in the vicinity of US$ 16 billions. Also, the economic loses of the buildings were approximately about US$ 5 billions. In the view of the large damage suffered in these earthquakes, the Turkish Earthquake Resistant Design Code is improved to protect life and reduce damage to an acceptable level.

Structural behavior and performance under a given earthquake loading, risk and probability must be considered when defining adequate design criteria. The costs and loses from possible future earthquakes and the difficulty in repairing the post earthquake damage, suggest the need for consideration of damage control in the design rather than just for life loss prevention. This can be taken into account by the development of design criteria which balances the initial cost of the building with the expected potential loses from future earthquake damages.

In building construction, primary concerns are design of the building, construction technique and building construction cost. These significant concerns are not the only concerns that should be addressed when planning for the future. In order to investigate the economics of facility management, the cost of building operations over the life of a building should be taken into account as well. The sum of initial and future costs associated with the construction and operation of a building over a period of life time is determined by using life cycle cost analysis.

The aim of this study is to determine the optimum design base shear value using life cycle cost analysis. For this purpose, a moment-resisting steel building is designed by using various base shear values. Initial costs, the cost of the damages and the total life cycle costs are estimated. The optimum economic design of the building is obtained using yield base shear and total cost values.

2 PERFORMANCE BASED DESIGN

Performance based building design is a general structural design philosophy in which the design criteria is chosen with respect to the selected performance level under various seismic motions. The important aim of the contemporary seismic design is not only protecting the human life but also accounting the additional performance targets. The advances in computer technology within the last decades made possible to employ more complex and realistic design procedures based on nonlinear analysis instead of conventional linear analysis.

Performance based design concepts have been introduced by various guidelines such as SEAOC Vision 2000 (1995), ATC-40 (1996), FEMA-356 (2000), FEMA-440 (2005). The main objective is to increase the safety against earthquakes to make them having a predictable and reliable performance. There are various types of analysis methods for assessing the structural performance level of buildings. Guidelines generally suggest the use of linear static, nonlinear static, linear dynamic, and nonlinear dynamic analysis procedures. However, the most popular analysis method is the nonlinear static analysis which is also known as pushover analysis. Pushover analysis is very efficient method for the direct evaluation of the structural performance at each limit-state.

The aim of the pushover analysis is to assess the structural performance in terms of strength and deformation capacity. Pushover analysis is based on the assumption that the response of the building is related to the response of an equivalent single degree of freedom system with properties proportional to the fundamental mode of the building. Using the analysis results, the sequence of member yielding, inelastic deformation amount of critical members, maximum interstorey drifts and the possible collapse mechanisms of the building can be identified.

The pushover analysis starts after application of gravity loads. A lateral load distribution is generally chosen proportional to the fundamental mode of the building. The building model is pushed using the predefined fixed lateral load pattern and total lateral load is incremented up to the lateral displacement of the control node reaches to the displacement demand of the selected earthquake level. The displacement demand of earthquake which is also called as the target displacement can be obtained from the FEMA-356 (2000) formula depending on the performance level considered.

$$\delta_t = C_0\, C_1\, C_2\, C_3\, S_a \frac{T_e^2}{4\,\pi^2}\, g \tag{1}$$

where T_e is the effective fundamental period of the building in the direction under consideration; S_a is the response spectrum acceleration corresponding to the T_e period, normalized by g; $C_0\, C_1\, C_2\, C_3$ are modification coefficients of displacement demand of earthquake.

The pushover curve, which is obtained with the end of the pushover analysis, is converted to a bilinear curve with a horizontal post-yield branch that balances the area below and above the pushover curve and the yield base shear of building is determined.

Using a single fundamental mode dominated load pattern in a pushover analysis may provide satisfactory estimation of the maximum interstorey drift when it occurs at the lower storey levels for regular buildings. When the maximum interstorey drift occurs at upper storey levels where higher mode contributions are significant, errors may become very large. In last years, some extensions to account for higher mode effects have been proposed and contributions to pushover procedures are still an ongoing research process (Aydinoglu, 2003; Chopra & Gupta, 2002).

3 EVALUATION OF LIFE CYCLE COST

The life cycle cost of a steel building can be considered as the sum of many different cost components. Cost of planning and design, cost of structural materials, cost of fabrication such as connection of members, cost of transporting fabricated pieces to the construction field, cost of handling, storage costs of rolled sections are basic initial costs. Erection cost, cost of tool operations and machinery on the construction site, cost of preparing the project site including the cost of preparing the foundations are also parts of the initial cost functions. In general, initial cost functions depend on the design intensity. The nonstructural component costs, such as those of partitioning, which may be high but do not depend on design intensity, were therefore, generally not considered as initial cost components.

There are other cost components which are generally accounted in life cycle cost calculations. Maintenance cost such as painting of exposed members of a steel building, inspection cost to prevent a potentially major damage to the building, repair cost, operating cost required for proper functional use of the building such as heating and electricity, damage cost based on an acceptable probability of failure, demolishing costs are some of the other cost components beside the initial costs.

In recent years, the limit state cost functions which is also an important part of the life cycle cost analysis have gained importance. The term limit state cost functions consists of the potential damage cost from earthquakes that may occur during the lifespan of the building. Limit state cost functions neglects other expenses which are not related to earthquake damages, such as maintenance costs. The limit state dependent cost functions mainly consists of damage cost, loss of contents, relocation cost, economic loss which is sum of rental and income loss, cost of injury, and cost of human fatality, and other direct or indirect economic losses. FEMA 255 (1994), FEMA 256 (1994) and ATC-13 (1985) can be used in limit state dependent cost functions calculations. In the present paper, evaluation of the damage cost due to earthquake occurrence is mainly focused and other cost components are neglected in order to monitor the damage cost effect on the life cycle cost.

The expected life cycle cost function under a single hazard can be calculated by the formula given below (Wen & Kang, 2001a):

$$E[C(t,x)] = C_0 + \left(C_1P_1 + C_2P_2 + \ldots + C_kP_k\right)\frac{\upsilon}{\lambda}\left(1 - e^{-\lambda t}\right) \tag{2}$$

where; P_k is the probability of the k^{th} damage state being violated given the earthquake occurrence and C_k is the corresponding cost; C_0 is the initial cost; λ is the annual momentary discount rate considered to be constant; υ the annual occurrence rate of significant earthquakes; and t is the service life of a building.

Damage states are defined according to the maximum interstorey drift of a building and limit values of each damage state is listed in Table 1 (Wen & Kang, 2001b). The cost of each damage state is described as a percentage of the initial cost and shown in the same table as well.

Table 1. Performance Levels and Damage Costs of a Building in Terms of Interstorey Drift Ratio*

Performance Level	Damage State	Interstorey Drift Ratio (%)	Cost % of Initial Cost
I	None	$\Delta<0.2$	0
II	Slight	$0.2<\Delta<0.5$	0.5
III	Light	$0.5<\Delta<0.7$	5
IV	Moderate	$0.7<\Delta<1.5$	20
V	Heavy	$1.5<\Delta<2.5$	45
VI	Major	$2.5<\Delta<5$	80
VII	Destroyed	$\Delta<5$	100

*ATC-13 (1985)

The probability of each damage state is calculated with the following equation:

$$P_i = P_i(\Delta > \Delta_i) - P_{i+1}(\Delta > \Delta_{i+1}) \tag{3}$$

According to Poisson's law, the annual probability of exceedance of an earthquake is given by the formula (Wen, 2001):

$$P_i(\Delta > \Delta_i) = (-1/t)\ln\left(1 - \overline{P}_i(\Delta > \Delta_i)\right) \tag{4}$$

where is the annual exceedance probability of the maximum interstorey drift value Δ_i.
The annual exceedance probability of the i^{th} damage state is obtained as:

$$\overline{P}_i(\Delta - \Delta_i) = a\, e^{-b\Delta_i} \tag{5}$$

The parameters a and b are obtained by best fit of known pairs. These pairs correspond to the earthquakes which probability of exceedance in 50 years is 2%, 10%, and 50%, respectively.

4 NUMERICAL EXAMPLE

A five storey moment resisting steel frame office building with the base area dimensions of 30.00 m x 24.00 m and 3.00 m storey height is considered. The structural model of the building is shown in Figure 1. The frame sections used for the designs of the steel buildings are limited with IPE and HEB profiles. Beams of floors are chosen from IPE profiles and all the beams of one floor are assumed to have the same type of section. However, columns are chosen from HEB profiles and all the columns of one storey is assumed to be designed with the same type of section as seen in Table 2. All members of the steel buildings are designed by using TS 648 and Turkish Earthquake Resistant Design Code. The modulus of elasticity is equal to E= 210000 MPa and the yield stress is f_y= 235 MPa. Steel frames are assumed to have rigid connections and fixed supports. Reinforced concrete is used in floor slabs and live loads are taken as 2.00 kN/m^2.

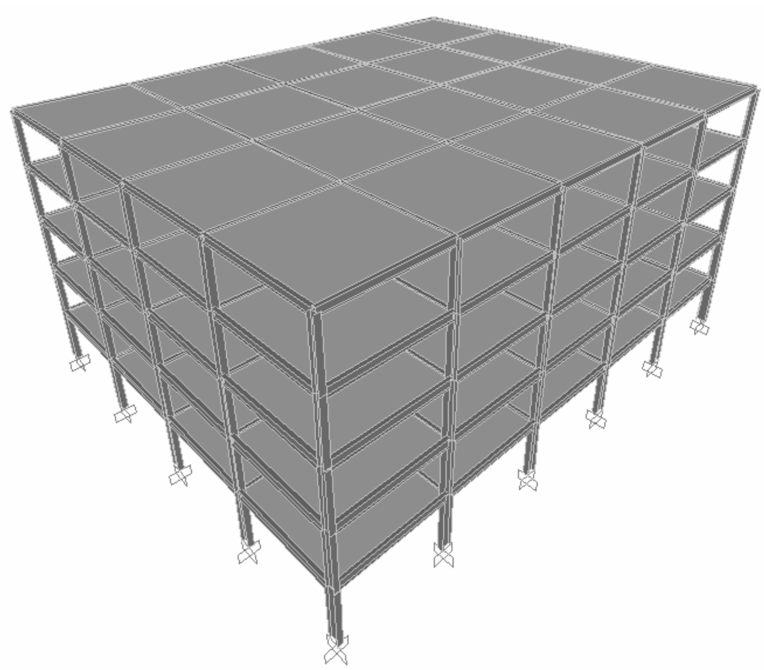

Figure 1. Five storey steel building

Table 2. Beam and column sections of designed steel buildings

Storey	Type	Design1	Design2	Design3	Design4	Design5
5	Column	HEB200	HEB200	HEB220	HEB240	HEB260
	Beam	IPE360	IPE360	IPE360	IPE360	IPE360
4	Column	HEB200	HEB220	HEB220	HEB240	HEB280
	Beam	IPE360	IPE360	IPE360	IPE360	IPE360
3	Column	HEB220	HEB220	HEB240	HEB280	HEB340
	Beam	IPE360	IPE360	IPE360	IPE360	IPE400
2	Column	HEB240	HEB240	HEB260	HEB300	HEB400
	Beam	IPE360	IPE360	IPE360	IPE360	IPE450
1	Column	HEB260	HEB260	HEB260	HEB320	HEB450
	Beam	IPE360	IPE360	IPE360	IPE360	IPE450

Table 2. Beam and column sections of designed steel buildings (Continue)

Storey	Type	Design6	Design7	Design8	Design9
5	Column	HEB300	HEB300	HEB320	HEB360
	Beam	IPE360	IPE360	IPE360	IPE360
4	Column	HEB300	HEB340	HEB400	HEB500
	Beam	IPE360	IPE400	IPE450	IPE500
3	Column	HEB400	HEB500	HEB650	HEB700
	Beam	IPE450	IPE450	IPE500	IPE550
2	Column	HEB450	HEB600	HEB700	HEB900
	Beam	IPE500	IPE500	IPE600	IPE600
1	Column	HEB500	HEB600	HEB700	HEB900
	Beam	IPE500	IPE500	IPE600	IPE600

In pushover analysis, Sap2000 (2006) is used and the lateral load distribution is chosen proportional to the fundamental mode of the buildings. Total lateral load is incremented up to lateral displacement of control node reach to the displacement demand of the selected earthquake level. The pushover curves converted to bilinear curves with a horizontal post-yield branch that balances the area below and above the pushover curves and then the yield base shear of buildings are obtained. The displacement demand of earthquake which is also called as target displacement is obtained from the FEMA-356 (2000) equations.

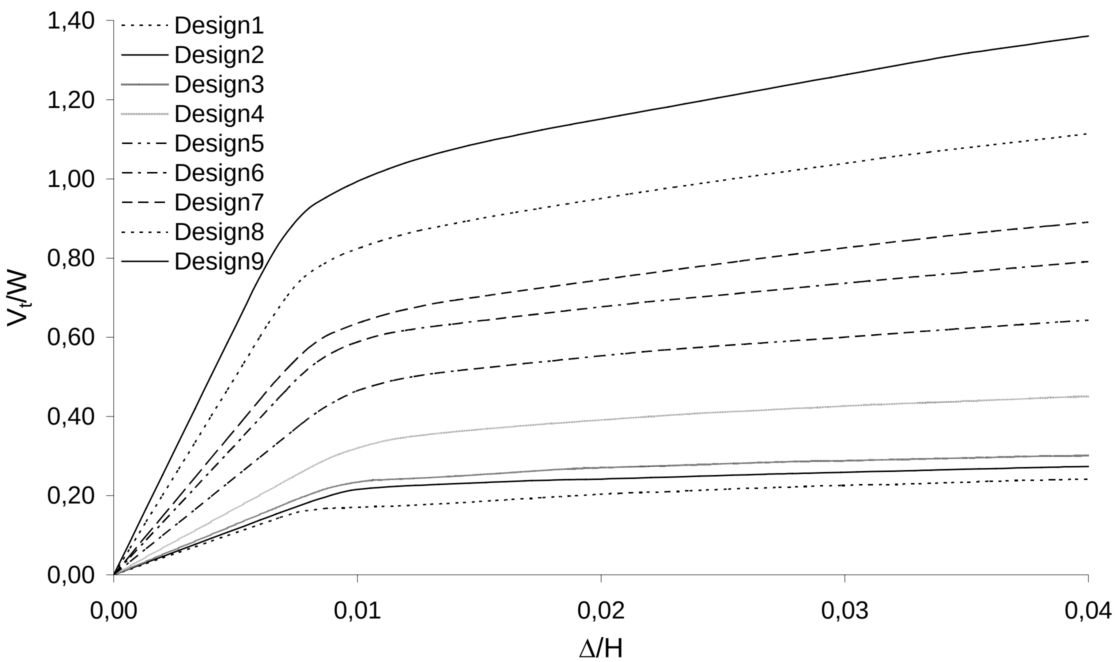

Figure 2. Static pushover curves of steel buildings

The calculation of the life cycle cost function for each design is also determined separately. The life cycle cost function calculation steps are given in details for the Building Design 6 in order to show the procedure clearly. From pushover analysis, three pairs of maximum interstorey drift are obtained and the annual probability of exceedance of an earthquake with a probability of exceedance %2, %10 and %50 in 50 years are calculated as $\overline{P}_{2\%} = 0{,}000404$, $\overline{P}_{10\%} = 0{,}0021$, $\overline{P}_{50\%} = 0{,}0139$. Using the maximum interstorey drifts and annual probability of exceedance values, $(\Delta_i - \overline{P}_i)$ pairs correspond to the three hazard levels with the given annual probabilities of exceedance is used to obtain the curve by an exponential function which is fitted by performing regression analysis. Once the function of the curve is plotted, annual probabilities of exceedance for seven damage states can be interpolated easily by using Figure 6. The values can be substituted to Equation 2 to calculate the values of life cycle cost functions.

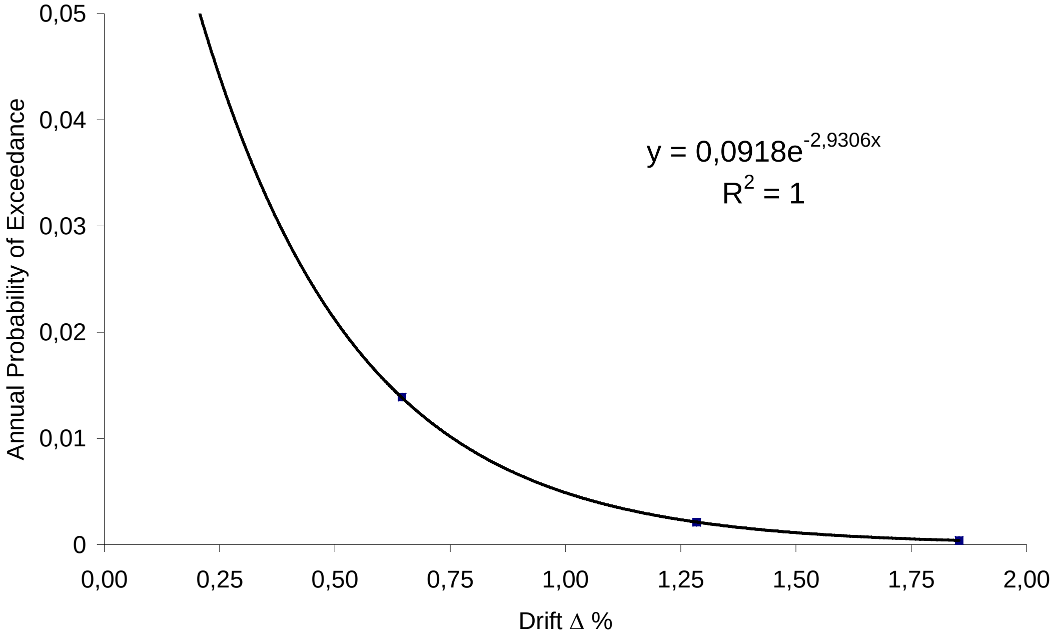

Figure 3. Calculation of annual probability of exceedance for each damage state design (Design 6)

Total expected damage cost is equal to the sum of the cost functions multiplied by the corresponding limit state probabilities. The optimal system yield force coefficient S_y can be calculated as the ratio of yield base shear force over weight of the building. A polynomial is used to fit the cost function and the optimal point for the life cycle cost is determined. The optimal system yield force coefficient S_y is found to be approximately 0.30 without considering human injury and death as shown in Figure 4.

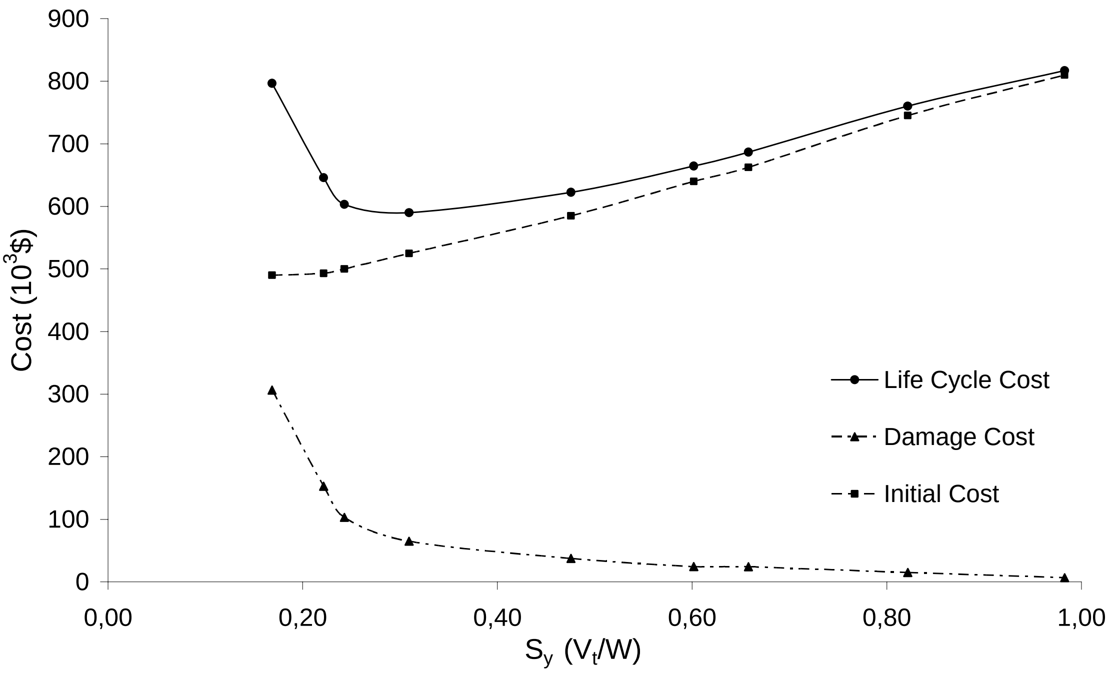

Figure 4. Total expected life cycle cost as a function of system yield force coefficient

5 CONCLUSIONS

The performance based design of steel buildings using life cycle cost analysis is investigated. Static pushover analysis performed during the cost analysis phase to determine the level of damage for different earthquake intensities. The cost analysis is based on initial material weight and earthquake induced life cycle cost. For the numerical example a five storey moment resisting steel office building is designed with various base shear values. Initial costs and damage costs are calculated in order to monitor the life cycle costs. The optimal system yield force coefficient is found to be approximately 0.30 using life cycle cost analysis. When the structural design is performed with single objective of minimizing the material weight, the resulting design will may be easily damaged with future earthquakes leading to much higher cost during the lifetime of the building.

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