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A risk-based framework for design of concrete structures against earthquake

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Abstract. Optimal design of structures against earthquake loads is often limited to reduce initial construction costs, while the cost induced to structures during their useful life may be several times greater than the initial costs. Therefore, it is necessary to consider the indirect costs due to earthquakes in the design process. In this research, an integrated methodology for calculating life cycle cost (LCC) of moment-resisting concrete frames is presented. Increasing seismic safety of structures and reducing human casualties can play an important role in determining the optimal design. Costs incurred for structures are added to the costs of construction, including the costs of reconstruction, financial losses due to the time spent on reconstruction, interruption in building functionality, the value of people's life or disability, and content loss are a major part of the future costs. In this research, fifty years of useful life of structures from the beginning of the construction is considered as the life cycle. These costs should be considered as factors of calculating indirect costs of a structure. The results of this work represent the life cycle cost of a 4 story, 7 story, and 10 story moment-resisting concrete frame by details. This methodology is developed based on the economic conditions of Iran in 2016 and for the case of Tehran city.

Keywords: quantitative risk; seismic design; optimal design; life cycle cost; indirect costs; financial losses; concrete structures

1. Introduction

In recent years, financial losses and social impacts of natural disasters have led to the need for advanced design methods. The new methods are able to reduce the negative consequences, as well as mortality and injuries, to acceptable levels. Expected loss caused by earthquakes is suggested as an important parameter in the seismic design of structures and decision-making process. Iran is located on one of the world earthquake belts, so many destructive earthquakes have occurred in Iran, which has often caused severe financial losses and casualties.

Seismic design codes for buildings were developed based on life safety criteria. Considering the life cycle cost of buildings along with life safety in design codes can improve the performance of structures. In this case, during and after an earthquake, buildings and residents suffer less damage in addition to ensuring the lives of residents. The possible seismic loss could be defined in terms of expected costs, interruption in building functionality and occupancy, and the risk of casualties. Investors always seek to reduce costs, while engineers are looking to present a design with maximum safety. By defining the quantitative parameters resulting from damage loss and expressing corresponding costs, the communication between decision-makers and design engineers will be simpler.

Principles of life cycle cost analysis (LCCA) are based on economic theories, and it is possible to design structures and make decisions on investment in industrial and commercial projects through this method. This method is widely used in transportation projects and water and energy resources conservation projects. The main application of life cycle cost in construction projects is related to seismic rehabilitation of structures (Vitiello *et al*. 2016). So, LCCA can be used as a criterion for evaluating the performance of structures. Also, the damage caused by a possible earthquake can be considered in calculations related to seismic optimization and decision making.

In the early 1960s, LCCA in the economic field was used to design products based on development, production, and retirement costs (Lagaros and Magoula 2011). In a similar study in 1996, it was shown that 40% of municipalities of the United States metropolises had used the LCC methodology over 20 years to evaluate their projects (Arditi and Messiha 1996). The life cycle cost of infrastructure was introduced in the early 1980s as a pricing and valuation tool for determining the total cost of ownership over the useful life of an asset in the United States (Asiedu and Gu 1998).

Initial research on building cost optimization has focused on the initial cost of the structure construction. However, in recent years, minimizing the life cycle cost, which includes the initial costs and expected costs due to earthquakes, attracted researchers' attention. For the first time, Liu and Neghabat (1972) considered the cost of earthquake damage in the design of the structure. Wen and Kang (2001) performed a sensitivity analysis to find the optimal model with minimum LCC by investigating damages to the building. The most important parameters in this study were losses due to casualties and injuries, and the discount rate. LCCA in construction projects was

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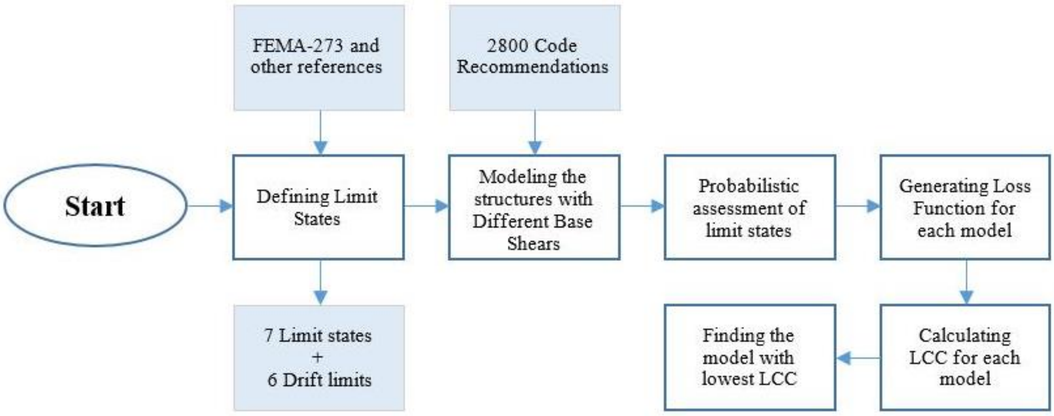


Fig. 1 The flowchart of finding the model with minimum life cycle cost

considered as a complex valuation tool based on structural performance (Kshirsagar *et al*. 2010). The life quality index was used in the optimization process in order to improve the structural performance and save people lives (Sánchez-Silva and Rackwitz 2004).

Considering initial cost and seismic loss as objective functions in the life cycle of moment-resisting steel frames, a two-objective optimization process for performance-based seismic design was proposed by Liu *et al.* (2003). Lagaros *et al*. (2006) used the cost correlated to limit states for comparing code design methods with performance-based design methods. Kohno and Collins (2011) studied the optimization of life cycle cost in concrete structures using HAZUS method. Kaveh *et al*. (2014) developed a practical and automated framework for the optimum performance-based design of steel moment-frame structures with an acceptable computational time. Minimization of the life-cycle cost is considered by treating the initial and the seismic damage cost as two separate objectives of the optimization problem. Uddin and Mousa (2011) determined the relative displacement of floors in timber structures by defining the design objectives based on limit states. Life cycle cost functions are becoming more accurate as time passes. In the study of Li *et al*. (2009), the optimum design model to minimize the expected life-cycle cost for ice-resistant platforms based on cost-effectiveness criterion is proposed. Multiple performance demands under ice load, such as those of the structure, facilities and crew members, are treated. The related failure evaluation criteria, costs of construction, consequences of structural failure modes are formulated, in which the damage loss, repair cost, death and injury loss as well as discounting cost over time are considered. Marzouk *et al*. (2014) presented an Integrated Life Cycle Bridge Information Modeling that can be used throughout different phases of the bridge life cycle including: design, construction, and operation and maintenance phases.

Although designs that are based on life cycle cost require more initial cost, designing on this basis can lead to more economic plans over the useful life of the structure. This study, for the first time in Iran, proposes a method to calculate the secondary cost components of buildings and show that these costs can help to find a more accurate life cycle costs of a building.

The above-mentioned points indicate that by considering the indirect costs of buildings in the design and planning process, their LCC could be minimized. The main goal of LCCA is to reduce adverse social, economic, and environmental impacts of structural damage after an earthquake. Finding a suitable method for finding the optimal economic design of buildings on their life cycle is an important step to reduce these adverse effects. The purpose of this study is to provide a method for calculating life cycle cost components considering the economic conditions of Iran, and for the case of Tehran.

2. Methodology

The theories and methods utilized in this study for structural design, structural performance assessment, and life cycle cost analysis are described in this section. The cost components were generally calculated based on the indicators related to Iran’s economic condition. In general, the procedure for conducting this research can be summarized in Fig. 1.

Prescriptive design methods generally do not provide reasonable reliability on the performance of structures at various hazard levels that may occur over their life cycle. Compared to the prescriptive methods, performance-based design criteria are described in terms of the parameters which reflect structural performance levels. In this method, structures are expected to meet some predefined performance levels at any seismic hazard with a specific intensity. Structural performance levels can be addressed by stress on structural elements, force in members, displacement at different points of the structure, and damage state of structural elements. Researches have been done to determine the maximum allowable values of structural response parameters (Heidebrecht 2011), (Ghobarah *et al.* 1997).

FEMA-350 provides a probabilistic method for performance-based design of new moment-resisting concrete frames, in which the variability of ground motion and the uncertainties in structural analysis are implicitly considered. FEMA-350 considers two performance levels for structural performance: Collapse Prevention (CP) and Immediate Occupancy (IO). Besides, Life Safety (LS)

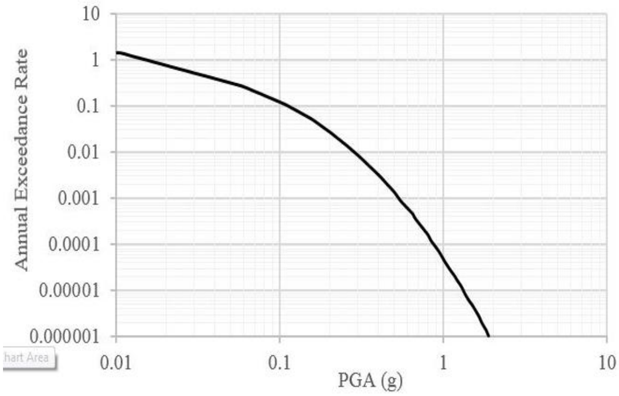


Fig. 2 Seismic hazard curve of Tehran

denotes a damage state where the structure experience significant damages, while it has a safe margin until the overall or partial collapse occurs. Therefore, based on FEMA-350, the performance objective used for intermediate moment frames is to achieve IO, LS, and CP at the hazard levels corresponding to the exceedance probability of 50%, 10% and 2% in 50 years, respectively.

According to Poisson's law, the probability of an annual exceedance rate of an earthquake with an exceedance probability of p in t years is given by the following equation

$$P = \frac{-1}{t}\ln\left(1-p\right) \tag{1}$$

Where P is the probability of annual exceedance rate of the earthquake. This rate is equal to the inverse of the return period (T) of that earthquake

$$P = \frac{1}{T} \tag{2}$$

The exceedance probabilities of 50%, 10% and 2% in 50 years correspond to the earthquakes with a return period of 72, 475, and 2475 years, respectively. To calculate the base shear corresponding to these annual exceedance rates, the seismic hazard spectrum of Tehran were used. Using the hazard curve presented for Tehran, the PGAs of earthquakes with different return periods and their annual exceedance rate can be obtained. The seismic hazard curve of Tehran is shown in Fig. 2 (Tsang *et al.* 2010).

The PGA corresponding to the design based earthquake in accordance with Iran seismic code is 0.385g. According to Fig. 2, the PGA for the earthquakes with an annual exceedance probability of $\frac{1}{2475}$ and $\frac{1}{72}$ are 0.58 and 0.18, respectively. Then, by obtaining the ratio of this PGAs to the PGA of the design-based earthquake, the spectrum would be scaled for each seismic hazard. Finally, using the generated spectra, the base shear corresponding to each seismic hazard would be obtained.

3. Life cycle cost

Total cost of a structure over its life cycle must include construction costs in addition to secondary costs. Secondary costs include reconstruction costs, financial losses, and losses due to injuries and death of resident, in the case that the structure is damaged. According to the high seismicity of Iran, secondary costs would incorporate the major part of total costs. In this research, these costs and probable losses were determined for the case of Iran, which are separately evaluated in the following sections.

LCC of a structure is equal to the sum of the present value of all expected costs associated with its management and maintenance during its life cycle. Also, life cycle costs can be related to the losses due to natural disasters such as earthquakes or storms. In fact, life cycle cost is associated with all possible costs that may affect the performance of the structure. Therefore, structures should be designed considering direct and indirect costs, including structural damage, social impact, and human injuries (Sánchez-Silva and Rackwitz 2004). Matta (2015) applied the LCC concept, instead of merely looking at an asset in terms of costs to design and build, investors and managers can broaden their perspective including all operation, maintenance, repair, replacement and disposal costs over a period of time (lifetime cost). The sum of the initial and the lifetime costs determines the total LCC of the building, whose minimization should be the primary goal of any optimal design action, either in constructing a new structure or in retrofitting an existing one. In order to calculate life cycle cost, the costs due to seismic hazards over the life cycle of structures were considered in the present research.

The total cost of a structure is referred to the life cycle cost of a new structure or the costs of the remaining life of an existing or rehabilitated one. Thus, LCC can be expressed as a function of time and design vector (Wen and Kang 2011)

$$C_{Tot}(t,s) = C_{In}(s) + C_{LC}(t,s) \tag{3}$$

where C_{In} is the initial cost of construction, C_{LC} is the current value of secondary costs and C_{Tot} is the total cost. s is the design vector corresponding to the loads and materials which affect the structural performance, and t denotes time. The initial cost component is related to the construction of a new structure, and C_{LC} is the expected cost of structural damage due to possible earthquakes over the life cycle of a structure.

The parameter used to determine different limit states was the maximum drift of structures. Performing life cycle cost calculations requires some relationships that convert the structural response to the damage states and define its corresponding costs. The damage states presented by ATC-13 are specified in Table 1, which can be used for

Table 1 Definition of structural performance levels and corresponding damage states

Performance level	Damage State	Allowable drift (%)
I	None	Δ<0.2
II	Slight	0.2<Δ<0.5
III	Light	0.5<Δ<0.7
IV	Moderate	0.7<Δ<1.5
V	Heavy	1.5<Δ<2.5
VI	Major	2.5<Δ<5.0
VII	Destroyed	Δ>5.0

Table 2 Calculation of costs according to FEMA 227 and 228

Variable	Cost	Equation	Basic cost
C^{dam}_j	Damage/ repair	Replacement cost×floor area×mean damage index	Replacement $85/sq ft
C^{con}_j	Loss of contents	Unit contents loss×floor area×mean damage index	Contents $28.9/sq ft
C^{rel}	Relocation	Relocation cost×gross leasable area×loss of time	$1.5/month/sq ft
C^{eco}_j	Economic loss	Rental cost+income cost	-
C^{ren}_j	Rental	Rental rate×gross leasable area×loss of function	$0.58/month/sq ft
C^{inc}	Income	Rental rate×gross leasable area×down time	$100/year/sq ft
C^{inj}_j	Injury	Injury cost per person× expected injury rate	$\$10^3$ /minor $\$10^4$/serious
C^{fat}_j	Human fatality	Death cost per person× expected death rate	$\$1.74\times10^6$ /person

determining the performance level of the structure.

By applying three seismic intensities (See section 2) to the models and extracting the drifts, the damage state of that model was determined for each earthquake event. Once the damage state is obtained, the seismic loss of the model can be calculated. An important assumption in life cycle cost estimation is that the consequences of an earthquake over the service life of structures are not related to any potential damage in previous events.

Secondary costs correspond to future events that occur at different times. However, the initial costs of construction should be pay at the beginning, so they could not be simply compared to secondary costs. Therefore, it is necessary to convert the secondary costs to their equivalent present values with a specified discount rate in order to make them comparable with each other and with the initial costs. Secondary costs calculated according to FEMA 227 and 228 are brought below.

To provide a method to calculate life cycle cost in Tehran, it is needed to find the above mentioned criterion in the case of Tehran, then, a comparison between these factors can be drawn.

4. Initial cost (Construction cost)

The construction time and cost for different moment resisting concrete frames are not constant to be definitively used in the decision-making process. Time can be a factor in increasing or decreasing construction costs. Preparing a questionnaire and gathering information from construction industry experts and professionals can provide the average initial cost of moment-resisting concrete frame buildings. The first question in questionnaires asked about the time required to construct a residential building with a moment-resisting concrete frame in three types: 4-story, 7-story, and 10-story. These types can represent low-rise, mid-rise, and high-rise concrete moment structures. The next question was about the construction costs of a full structure. Also, the proportion of the cost of concrete frame to the total construction cost was questioned in order to obtain a good estimation for the initial cost of structural and non-structural elements.

According to the variable quality of materials and work in different companies, 25 contractor companies and engineers working in the construction industry were questioned in this research. Because some manufacturers do not have enough experience in the construction of concrete moment frame structures up to 10 floors, only 12 companies were able to answer all the questions. So, the data were analyzed from a sample of 12 questionnaires. The answers were separately evaluated for 4, 7, and 10-story buildings. The suggested costs were stated regardless of land price, construction license and other side fees, and considered only the construction costs. Experts were asked to calculate the costs by assuming that high-quality Iranian materials were utilized.

A questionnaire is valid when it measures exactly what a company really wants to know. Obtaining the price of construction of moment-resisting concrete residential buildings is completely accurate and limited to a particular type of structure. In addition, all companies that were asked, were working in Tehran and one of their executive officers answered the questions So, the questions in the questionnaire were completely appropriate for these respondents. The questionnaire here was qualitative and the questions were open ended. This is the simplest form of questionnaire. Experts' views were also obtained to verify the questionnaire. Therefore, this questionnaire had complete reliability and validity in the field of the study that was conducted.

Based on the experts' views, manufacturing price of concrete beams and columns accounts for about 9% of the total construction costs of a structure. By subtracting this portion of the cost from the total cost of construction, the result would approximately determine the cost of building construction (per square meter), regardless of concrete cost. Thus, by increasing the amount of concrete and strengthening the structure, along with determining the exact price of manufacturing the members, the total construction cost of the building can be obtained for each model. The price of concrete used in the construction of structures should be multiplied by a factor of 1.43, considering commonly used coefficients such as overhead cost allocation, contractors, region, and floors. The construction cost of a moment-resisting concrete frame regardless of concrete price could be calculated as follows

$$C_w = 0.91 \times C_c \tag{4}$$

Where C_c is the cost of constructing concrete frame buildings reported by engineers and experts (based on their experience), and C_W denotes the construction cost regardless of concrete price. According to the list price of 2016, the price of manufacturing concrete column and beam was $\$2.74/m^3$ and $\$2.54/m^3$, respectively (Schedule of Prices 2016). The prices suggested by building companies for constructing a 4, 7, and 10-story moment resisting concrete structures are shown in Table 3. The costs suggested by the companies are graphically depicted in Figs. 3-5.

The average price of construction for 4, 7, and 10-story

Table 3 Construction prices of concrete structures

Company #	Construction cost ($/m²)		
	4-story building	7-story building	10-story building
1	225	240	260
2	225	265	290
3	240	270	300
4	245	285	300
5	270	285	300
6	270	300	325
7	270	300	325
8	270	305	330
9	280	305	320
10	285	310	335
11	285	350	375
12	310	325	350

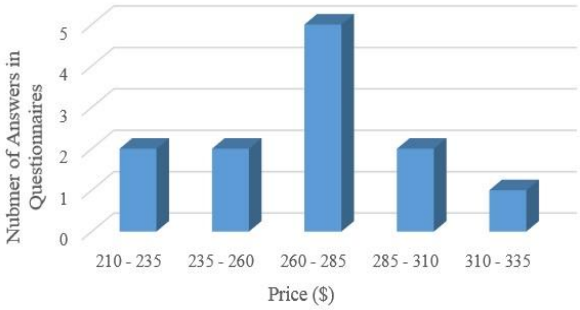


Fig. 3 The construction cost of a 4-story concrete structure

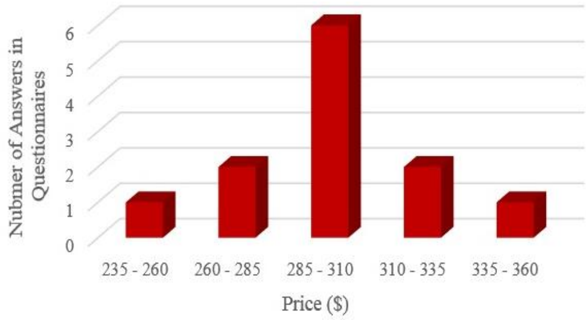


Fig. 4 The construction cost of a 7-story concrete structure

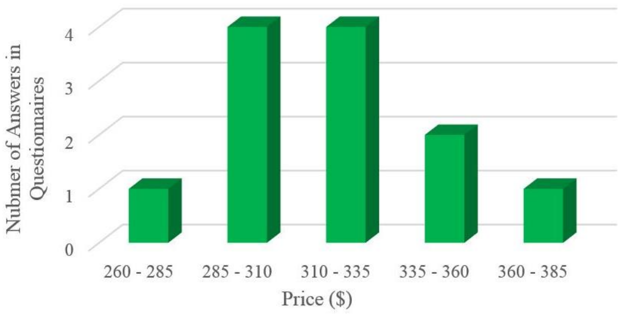


Fig. 5 The construction cost of a 10-story concrete structure

concrete frames is $265, $295, and $317 per square meter, respectively. This is approximately a third of price of construction that was calculated by FEMA 227 and 228. Net construction costs without considering the cost of concrete are calculated using Eq. (4)

$$\begin{aligned} C_{w,4-story} &= 0.91 \times 265 = \$241 \\ C_{w,7-story} &= 0.91 \times 295 = \$268 \\ C_{w,10-story} &= 0.91 \times 317 = \$288 \end{aligned} \tag{5}$$

The data presented in Table 4 shows the ratio of downtime associated with each damage state to the downtime of complete damage state. According to ATC-13, repair cost of a building is equal to a ratio of construction cost, so the repair cost in each damage state can be obtained by multiplying the mean damage factor (MDF) to the construction cost.

5. Downtime

After any natural disaster such as earthquake, a time duration is required to rebuild damaged structures or set up facilities. When an earthquake occurs on a large urban scale, the weaknesses in urban management, urban planning system, quality control of construction, and crisis management would become obvious, such as what happened after the earthquake of Bam, Iran in 2003. According to these concerns, the time needed to rebuild damaged buildings depends on many factors, which can prolong the reconstruction time of a damaged region. The factors include blockage of highways, lack of adequate budget, lack of expert human resources, inconsistencies, mismanagement and lack of proper crisis management during and after an earthquake.

To obtain a proper approximation for rebuilding time of a damaged structure, the next question asked in the questionnaires was related to the construction time of concrete structures. In this case, 4, 7, and 10-story structures have different construction times. By examining the questionnaire data on the construction time of

Table 4 ATC-13 and FEMA-227 recommendations for downtime and costs

Damage state	Mean damage state (%)	Interruption in building operation (%)	Expected fatality incidence	Expected minor injury	Expected major injury
I) None	0	0	0	0	0
II) Slight	0.5	0.9	4.0E-06	3.0E-05	1.0E-06
III) Light	5	3.33	4.0E-05	3.0E-04	1.0E-05
IV) Moderate	20	12.4	4.0E-04	3.0E-03	1.0E-04
V) Heavy	45	34.8	4.0E-03	3.0E-02	1.0E-03
VI) Major	80	65.4	4.0E-02	3.0E-01	1.0E-02
VII) Destroyed	100	100	4.0E-01	4.0E-01	2.0E-01

Table 5 Construction times of concrete structures

Company #	Construction time (months)		
	4-story building	7-story building	10-story building
1	8-12	12-18	18-22
2	12	18	24
3	14-16	20-24	28-32
4	12	15	18
5	12	16	21
6	8-10	12-14	15-19
7	10	16	22
8	12	18	24
9	18	24	30
10	8-10	15-18	20-23
11	10-14	16-20	22-26
12	12	18	24

Table 6 Interruptions in operation of buildings at each damage state based on ATC-13, and downtime of buildings

Damage state	Interruption in building operation (%)	Downtime of 4-story buildings (days)	Downtime of 7-story buildings (days)	Downtime of 10-story buildings (days)
I	0	0	0	0
II	0.9	3.3	4.6	6.3
III	3.33	12.2	17.2	23.3
IV	12.4	45.3	64	86.8
V	34.8	127	179	243.6
VI	65.4	365	515	700
VII	100	365	515	700

structures, building a 4-story moment resisting concrete frame with a floor area of 225 m^2 takes about 12 months.

Increasing the number of floors causes an increase in total construction time. Depending on project management, number of workers, and other conditions, construction time would change. Based on the information gathered from the questionnaires, the average time required to build a 7-story building is 17 months, and for a 10-story building is 23 months. The times presented by construction industry activists are shown in Table 5.

ATC-13 and FEMA-227 suggest downtime -the required time for rebuilding and re-utilization- for different types of buildings and structural systems based on damage states. FEMA-227 presents the downtime as a fixed number for each structural system. The expressed numbers do not have much to do with real conditions, and downtime can greatly vary depending on the circumstances, especially in Iran. ATC-13 describes downtime as a proportion of the required time to reconstruct a completely damaged structure.

In order to obtain more precise results in the case of Iran, a combination of the data presented in ATC-13 and the results obtained from the questionnaires was used. The time required to build a structure from the questionnaire was assumed to be equal to the reconstruction time of a completely destroyed structure. Finally, using ATC-13, the downtime at other damage levels was also obtained.

The time required for reconstruction and re-utilization of 4, 7, and 10-story structures at each damage state is shown

Table 7 Restoration time of damaged buildings in FEMA 227

Mean Time in Days to Restore to Given Percent of Function			
Central Damage Factor	30%	60%	100%
0.5	0.2	0.2	0.8
5	0.3	1.5	3.3
20	1.9	5.4	10.5
45	15.2	30.5	71.9
80	57.2	93.8	146.6
100	105.5	152.1	211.9

in Table 3. It was assumed that a structure at extreme damage state (VI) should be completely replaced with a new building, so the downtime associated with this damage state was assumed to be equal to the downtime of complete damage state.

Duration needed to restore the residential building is calculated by FEMA227 that is illustrated below.

By comparing the time of reconstruction in Iran and the time that was calculated in FEMA, it can be concluded that rehabilitation time in Iran is considerably more than that of USA.

6. Cost of interruption in building functionality

Interruptions in the functionality and occupancy of buildings induce additional costs to the residents. The minimum amount of these costs are being obtained by calculating the rental cost of the building and the compensatory cost for temporary relocation. This interruption becomes more important and crucial in commercial or office buildings because they serve a wider range of individuals and businesses.

Calculating the loss caused by interruptions in the occupancy of a damaged building requires knowing the average rental cost of residential units in Tehran. Due to the continuously changing prices, it is necessary to extract the average rental price from Iran Tenement Management Information System, which publishes comprehensive information for each season. According to this system, the average monthly rental price for a usual residential building with an area of 100m^2 in Tehran was about \$600/month in the second quarter of 2016. Accordingly, the average daily rental price in Tehran was \$0.2/m^2/day. Due to the need for temporary residence in an alternative place, residents are required to pay a rental for the second place. Thus, the loss caused by an interruption in the functionality of the building is equal to 0.2×2= \$0.4/m^2/day.

7. Casualty cost (The value of people's life)

Two main methods are commonly used for estimating the cost of early death in scientific researches:

- Human Capital Method (HCM)
- Willingness to Pay (WTP)

There are some advantages and disadvantages for both method, but WTP has recently become more commonplace

(Hensher *et al.* 2011). In HCM, evaluation of the losses due to an early death on the entire economy is taken into account. With his production, earnings, and consumption, a person plays an economic role in the community. Thus, by calculating production, income or consumption, the impact of each individual's economic activities could be estimated. However, in WTP, the amount of money a person is willing to pay to reduce his death risk is determined, and then the value of an individual's life can be estimated. The most important merit of WTP is to measure the beneficiary's preferences of any person. On the other hand, its disadvantage is its reliance on the income level of individuals.

Miller presented a method based on the gross domestic product (GDP) to estimate the average of a person life value in a community (2000). Based on this method, the value of life can be calculated in terms of GDP and community population. The value of a person's life in each country is equivalent to 120-140 times of GDP of the country. The result obtained from this method is considered as an average value for all people in the community (Eq. (6)). In the following equation, *VSL* denotes the value of people's life

$$VSL = 140 \times GDP\ /\ Capita \tag{6}$$

The data of GDP and GDP/capita for all countries is presented annually by various certified agencies, the most prestigious of which is the World Bank annual reports. According to the World Bank report, Iran's GDP/capita was \$5,219 in 2016. Based on Eq. (6), the average value of people's lives and, in fact, the loss to the country due to the death of a person in Iran, is obtained as follows

$$VSL_{Iran} = 140 \times \$5,219 = \$730,660 \tag{7}$$

Another significant factor to determine casualty loss is the number of people living in residential buildings. Residential area per capita is between 20 m^2 and 30 m^2 in the east and west of Tehran (Atlas of Tehran Metropolis 2016). Considering 25 m^2 as the index value, 0.04 person/m^2 are prone to earthquake hazard.

8. Injury and disability cost

The years that are lost due to an early death of a person or years of life that are accompanied by disability with a certain intensity and duration is called burden of disease or DALYs (Disability-adjusted life years). Thus, each DALY represents the loss of one year of a healthy life. Calculation of DALY for a disease has two components:

1. Total years of a person's life that is lost due to an early death because of a disease or injury.
2. Total years in which a person is suffering from the consequences of a disease or disability.

In order to calculate the years that are lost due to disease or injury, the age of the deceased is subtracted from the highest life expectancy of men and women around the world. Also, in order to determine the value of life of a person who is suffering from a particular illness, his condition is compared to a normal and healthy person. In other words, the disability weight should be determined for each scenario.

The disability weights for various injuries and diseases were presented by the Ministry of Health and Medical Education (Health Deputy Burden of Diseases and Injuries 2007) for the case of Iran. Similar data can be found in research by Stouthard (2000), in which the average disability weight for injuries is 0.21. Thus, considering the disability weight to be equal to 0.21, and assuming that the average age of severely injured people is 45 years, the loss caused by injuries could be calculated. The maximum life expectancy is 85 years, which is related to Japanese people. The procedure for determining the loss due to an early death or permanent disability are as follows:

1. The average age of severely injured people subtracted from maximum life expectancy

$$85 - 45 = 40 \tag{8}$$

2. The disability weight of remaining years:

$$40 \times 0.21 = 8.4 \tag{9}$$

3. The yearly value of a person's life according to the general value of people's lives (Eq. (7))

$$\$730,660 \div 85 = \$8,596 \tag{10}$$

4. Estimated loss due to continuing life with disability

$$8.4 \times \$8{,}596 = \$72{,}000 \tag{11}$$

This loss should be added up to the estimated cost of treating people with severe injuries. According to the cost calculation guidelines in FEMA-227, injuries are divided into two categories: minor and major. Reinhardt, *et al.* (2011) described that minor injuries caused by an earthquake include swelling, leg pain, muscle cramps, tendon inflammation, ulcer, and skeletal muscle pain. However, SCI (spinal cord injuries), TBI (traumatic brain injury), amputation, severe fractures, and crushing were noted as major injuries.

Data of the treatment price of injuries caused by an earthquake could be gathered by interviewing experts and specialists, as well as examining bills of trauma hospitals. The lack of appropriate and classified data in the organizations related to the Ministry of Health and Medical Education made it difficult to gather information about this type of costs. Therefore, by examining the price offered for treatment of similar cases in other countries and comparing the minimum wage in both countries, an appropriate approximation can be presented. Kang and Wen (2000) reported that the cost of treatment for minor injuries was \$1,000, and for major injuries was \$10,000 for the case of the United States. Given that the research was carried out in 2000, and considering the inflation rate between 2000 and 2016 in the calculations, the costs will change to \$1,435 and \$14,348.

It is estimated that the minimum wage in Iran is about one-seventh of the minimum wage in the United States. Accordingly, for the case of Iran, the cost of treatment for minor injuries is equal to \$205 and the cost of treatment for major injuries is \$2,050. By adding up the loss due to continuing life with a disability to the cost of treating major injuries, the total loss of injury and disability is \$74,250.

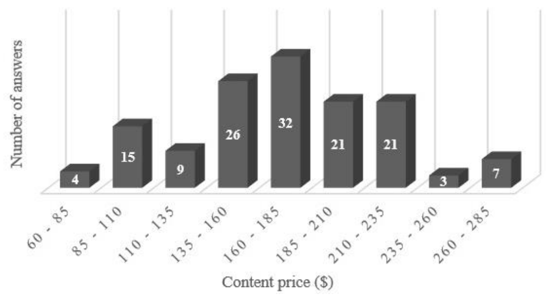


Fig. 6 The content price of residential buildings

9. Content loss

The contents of buildings are different depending on the type of building, city, neighborhood, and residents. Therefore, it is not rational to generalize a fixed number as the value of the contents for all buildings. To find the value of the contents per square meter, a questionnaire was prepared and given to people from different regions of Tehran. Families were requested to provide a list of home appliances along with their prices if needed to be replaced. The area of each house was also questioned in order to determine the loss caused by destruction of the contents per square meter.

The format of this questionnaire is similar to that of in section 4. It was qualitative and included open ended questions. Regarding the fact that there are no other statistics about value of contents in Iranian's houses, these findings are not comparable to any previous literature in the society of Tehran. So, its simplicity, focusing on the main target of acquiring prices, and experts' views are the main reasons of reliability and validity of this questionnaire.

In order to carry out this sampling, 480 questionnaires were provided to residents from different regions of northern, central and southern of Tehran. Because of the nature of questions, many persons decided not to disclose their private information and declined to respond. So, the information of 111 questionnaires was eventually categorized and analyzed. Fig. 6 shows the dispersal of people responds to the questionnaire. According to the results, the average value of indoor contents is \$165/m^2. The dispersion of prices can be due to the presence of different classes of society in the sample. According to table 2 the price of contents used in residential areas in USA is about \$309/ sq m. Therefore, a significant difference can be seen between these prices in Iran and USA.

10. Discount rate

In an investment planning, discount rate is typically used to convert the expected costs and incomes of the coming years, based on the event time, to their present value. In the present net value method, all costs and incomes are discounted at an appropriate interest rate depending on the time at which they are incurred

$$P = F\left[\frac{1}{(1+i)^n}\right] \tag{12}$$

where n is the event time in unit of years, i is the discount rate, F is the quantitative amount of a future cost or income based on cash flow, and P is the present net value of that cost or income.

Today, many economists and governments use social time preference rates to evaluate public projects (Abdol Abadi 2017). Based on this method, there are three main components for calculating the social discount rate, resulting in an equation known as Ramsey formula (Ramsey 1928)

$$s = m + e.g \tag{13}$$

In this case, s denotes social discount rate, m is mortality rate, e is absolute value of the elasticity of final consumption or income, and g is consumption growth rate per capita over a long period of time. Calculating each of these parameters requires extensive economic studies and analyzes. Due to the complexity of the factors in Equation 11, the values of discount rate are taken from the results of past researches. It was reported that the discount rate had been about 7.2% for the case of Iran, between 1984 and 2007 (Abdol Abadi 2017). This number is consistent with the results of ISO 156865, which categorizes the discount rate for most Asian countries between 5% and 8%.

11. Lifetime cost

Pacific Earthquake Engineering Research (PEER) introduced a method to measure the seismic performance of structures for performance-based earthquake engineering. In this approach, the concept of performance is separated into probabilistic models of seismic hazard, engineering demand parameter, damage, and loss. An equation is presented using the probability rule of sum, known as PEER triple integral (Cornell and Krawinkler 2000)

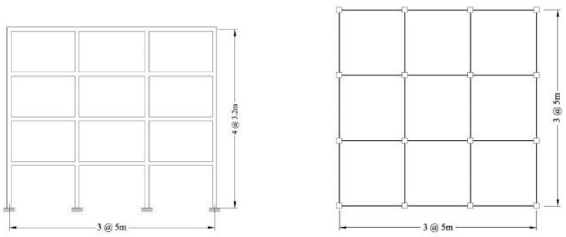
$$\lambda(DV > dv) = \int_{dm}\int_{edp}\int_{im} G\left(dv\,|dm\right)\left|dG\right. \\ \left(dm\,|edp\right)\left|\left|dG\left(edp\,|im\right)\right|\right|d\lambda\left(im\right)\right| \tag{14}$$

where im is a scale of intensity (e.g., spectral intensity), edp is an engineering demand parameter (e.g., drift), dm is a damage scale, and dv is a decision variable (e.g., cost).

The indirect costs of each model can be calculated by converting the costs associated with each year in future over the life cycle of the structure to their present value. By multiplying a coefficient to the sum of the annual secondary costs, the total secondary costs can be obtained for 50 years

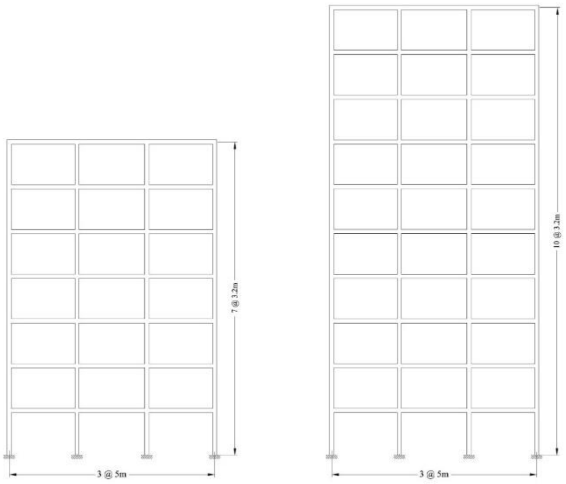
$$C_{UL} = \frac{1}{\lambda}(1 - e^{-\lambda t})C_{ID} \tag{15}$$

where CUL is total secondary cost of the building over its useful life, CID is annual secondary cost, λ is discount rate, and t is service life. Thus, by calculating the total present value of secondary costs and adding them up to the initial construction costs, the life cycle cost of the model can be obtained and compared to the LCC of other models.



(a) (b)

Fig. 7 Model geometry, (a) Typical floor plan of buildings (b) Frame view of 4-story building



(a) (b)

Fig. 8 Model geometry, (a) Frame view of 7-story building (b) Frame view of 10-story building

12. Structural modeling and optimization

As a case study, three types of concrete structures with 4, 7, and 10 stories and three spans in each direction were analyzed in this study. These cases represent low-rise, mid-rise, and high-rise buildings. The height of stories is 3.2 m and the length of each span is 5 m. An Intermediate moment frame was selected as the structural system, and the buildings were intended for residential use. The plan of the floors and the elevation view of the structures are shown in Figs. 7 and 8.

The magnitude of dead and live loads, which were uniformly applied on the area of each slab, was 750 kg/cm^2 and 200 kg/cm^2 for the floors (except the roof). Also, the magnitude of these loads for the roof was 500 kg/cm^2 and 150 kg/cm^2.

By calculating the secondary costs due to different earthquake intensities, a curve can be obtained with the best fit on single points. The area under this curve defines the indirect costs of each model in one year of its life cycle. The *y*-axis of the plot represents the annual secondary costs, and the *x*-axis denotes the probability of annual exceedance rate of each earthquake event. The total indirect cost can be calculated by converting all costs induced to the structure to their present value.

The equations of best-fitted curves were obtained by MATLAB software, and the optimal model could be determined using these equations. In other words, the base shear value of a model with minimum life cycle cost can be obtained.

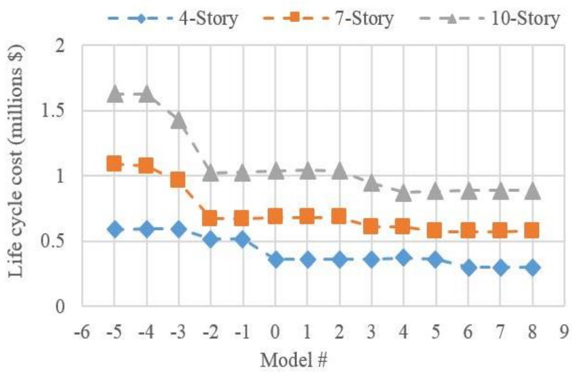


Fig. 9 Comparison of the LCC of concrete frames

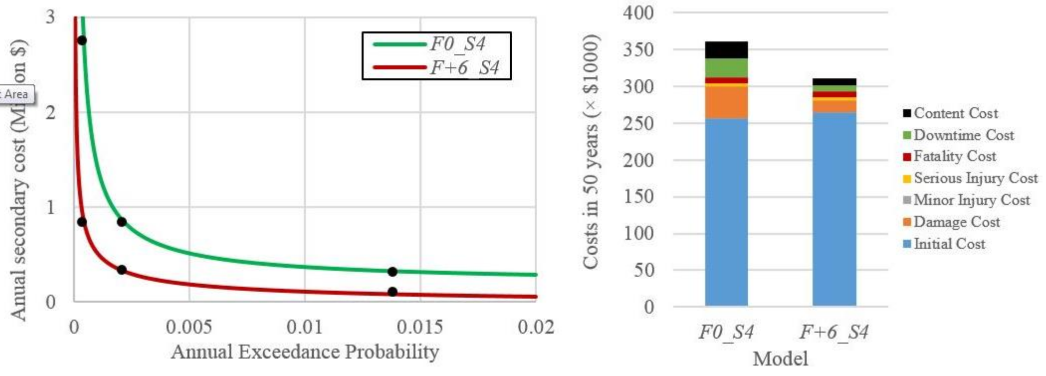
After designing the models with different base shear values and different floor numbers, three seismic load scenarios with 50%, 10% and 2% exceedance probability in 50 years were applied to them. By analyzing the models and calculating the maximum story drifts, their damage state was obtained. Given the damage state of each model under different seismic intensities, its annual secondary costs were calculated.

In each series of 4, 7, and 10-story structures, 14 models were designed with different base shears. The base shear values of 5 models were less than the prescriptive value of base shear, and 8 models had base shear values above that. *F*0 models represent the models which were designed based on the seismic code requirements. The other models were briefly named as *Fx_Sy*, where *x* is the intervals of increasing the base shear to the prescriptive value, and *y* represents the number of stories. For example, *F*+1_*S*4 is a 4-story model which its base shear is 10% more than the code base shear. The 4, 7, and 10-story models of moment-resisting concrete frames were designed with base shear values of 50% lower to 80% higher than its prescriptive value.

The optimal models of 4, 7, and 10-story structures were obtained by examining the life cycle cost of all models and comparing them. By drawing the secondary cost curve which is described in section 11, total indirect costs were obtained over the model service life.

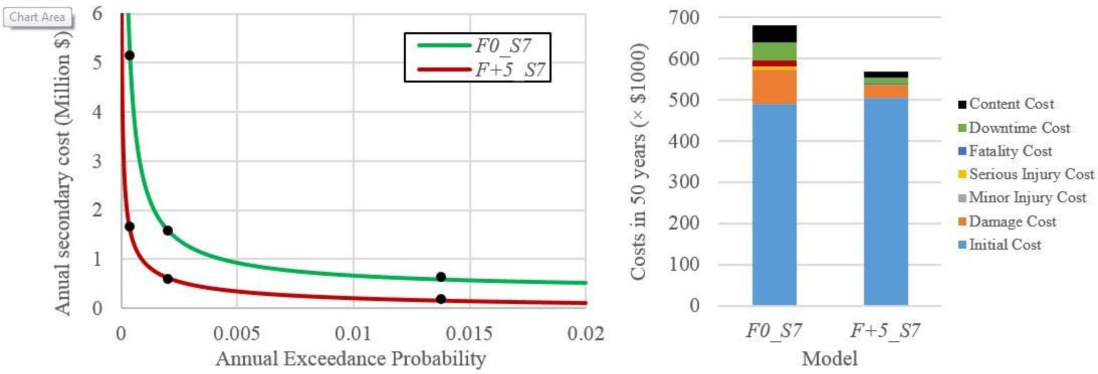
The results of life cycle cost assessment of 4-story buildings showed that the model with a base shear that is 60% more than what specified in code had the lowest LCC. This optimal model has 16.9% lower life cycle cost than the code-based design model. In the case of 7-story structures, it was found that the optimal model has a base shear that is 50% more than what specified in code, and it has 16.1% lower life cycle cost than the code-based design model. Also, for 10-story models, the base shear of the optimal model is 50% more than prescriptive value, and it had a 15.5% reduction in life cycle cost compared to the model designed according to code requirements.

Fig. 9 depicts the LCC of concrete moment frames with different base shears. The x-axis numbers are equivalent to *x* in *Fx_Sy*. The model number thus indicates the increase or



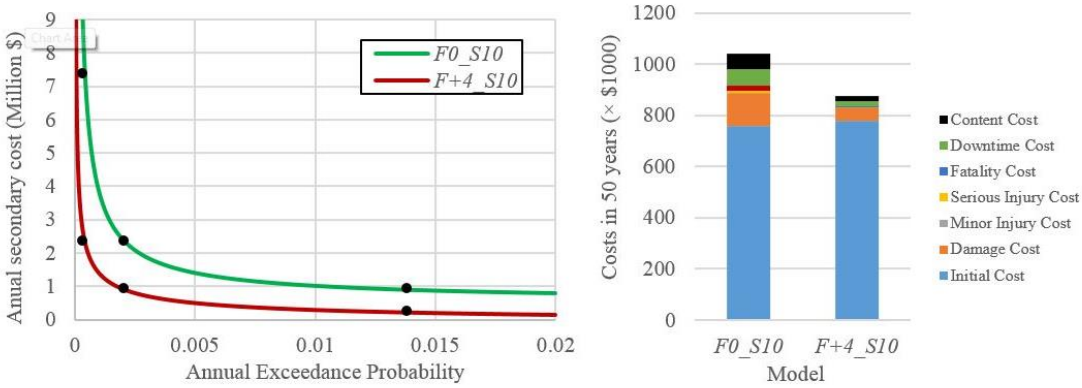
(a) (b)

Fig. 10 Cost assessment of code-based and optimal models of 4-story building: (a) Secondary cost curves, (b) Details of life cycle cost



(a) (b)

Fig. 11 Cost assessment of code-based and optimal models of 7-story building: (a) Secondary cost curves, (b) Details of life cycle cost



(a) (b)

Fig. 12 Cost assessment of code-based and optimal models of 10-story building: (a) Secondary cost curves, (b) Details of life cycle cost

Table 8 Cost evaluation for the models

Models		Annual secondary costs ($)	Total secondary costs ($)	Construction cost ($)	Life cycle cost ($)
4-story	*F0_S4*	7,665	103,549	256,649	360,198
	F+6_S4	2,606	35,203	264,123	299,326
7-story	*F0_S7*	13,934	188,235	490,266	678,501
	F+5_S7	4,761	64,324	504,471	568,795
10-story	*F0_S10*	20,623	278,607	757,772	1,036,379
	F+4_S10	7,087	95,743	780,071	875,814

decrease in the base shear. Table 8 shows the annual secondary costs, the total secondary costs over the service life, and LCC of the code-based and the optimal models. Also, the secondary cost curves and the details of life cycle cost of code-based and the optimal models are shown in Figs. 10-12. According to these figures, by a small increase in initial cost, the secondary cost was significantly reduced.

In a study conducted by Wan and Kang (2001), the secondary cost was calculated as $746,000 for an optimized

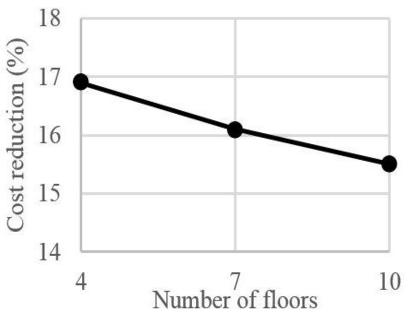


Fig. 13 Life cycle cost reduction in optimal models compared to code-based design models

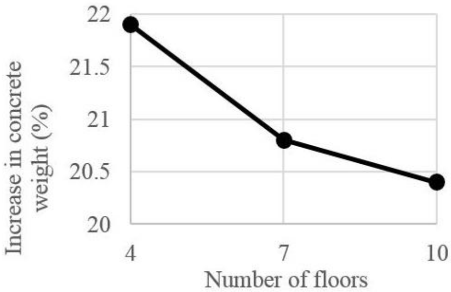


Fig. 14 Increase in concrete weight in optimal models compared to code-based design models

Table 9 Concrete weight of structural elements of 4, 7, and 10-story structures

Models		Concrete weight (kg)		
		Beam sections	Column Sections	Total
4-story	*F*0_*S*4	21,097	23,310	44,407
	F+6_*S*4	26,776	27,355	54,131
7-story	*F*0_*S*7	42,543	45,793	88,336
	F+5_*S*7	52,419	54,336	106,755
10-story	*F*0_*S*10	65,913	75,278	141,191
	F+4_*S*10	80,159	89,859	170,018

status of 9 story with each floor 1261 m^2 building in Los Angeles. Comparing the data driven from this mentioned study to findings from our study, \$65.73/sq m was depicted as secondary cost for an optimized 9 story building in Wen and Kang's study, while \$42.55/sq m is shown for an optimized 10 story building here. This difference in findings is reasonable through contrasts in economic parameters in Iran and USA. All calculated secondary cost units for the case of Iran were sensibly lower than that of USA, which was presented in FEMA 227 and 228. But rehabilitation time in Iran was considerably higher than that in USA. Hence, this lower secondary cost in Iran is reasonable.

Based on the results, the reduction in costs and the increase in concrete weight of the optimal models of each type of frames can be investigated and compared. As shown in Fig. 13, the cost reduction ratio is about 16%, but as the building gets taller, the optimal model has a lower cost reduction than the code-based model (Fig. 13). Also, the increase in concrete weight of element sections in the optimal model was 21.9% in 4-story buildings, 20.8% in 7-story structures, and 20.4% in 10-story structures (Fig. 14).

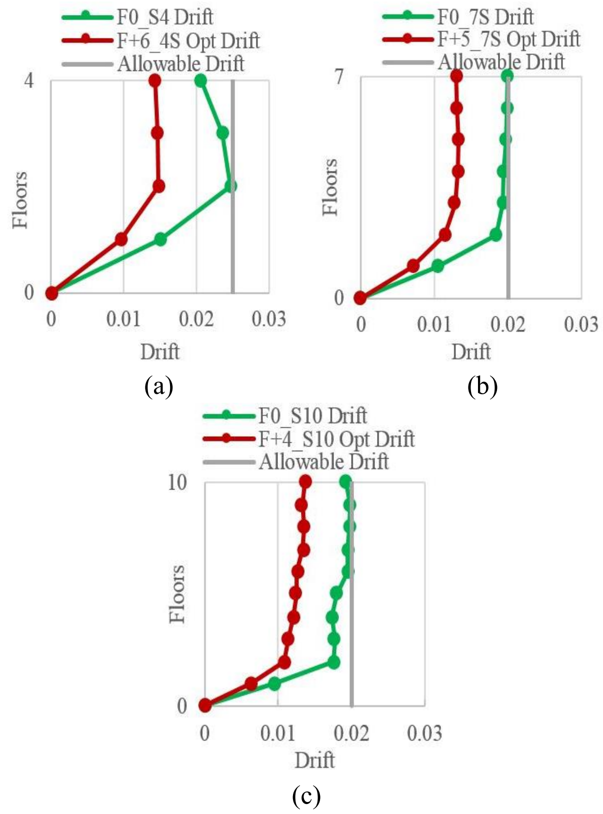


Fig. 15 Comparison of drifts in code-based and optimal design models: (a) 4-story building, (b) 7-story building, (c) 10-story building

The weight of concrete utilized in these models are specified in Table 9.

According to the LCC assessment, the results showed that the optimal model in three types of buildings with 4, 7 and, 10 floors was *F*+6_*S*4, *F*+5_*S*7, and *F*+4_*S*10, respectively. The Drift of the floors in three types of structures is plotted for the code-based and optimal design in Fig. 15. This figure shows that the drift values for both models were below the allowable limit.

13. Concluding remarks

In many optimization problems in structural engineering, problems become highly complicated due to a large number of variables and complex objective functions. As a result, solving optimization problems require a great deal of computational time and cost, which in many cases make the solving process impossible. Approximation methods can be implemented in this area as a remedy to achieve relatively accurate results. Life cycle cost based designs is introduced as one of the approximate methods. However, it is difficult to accurately predict secondary costs of a structure over 50 years of its useful life. This study attempts to improve the accuracy of the calculation of secondary costs.

By examining and evaluating the results of the questionnaires and based on the calculations on other economic parameters, the results are summarized as follows:

• The construction cost for a 4-story moment-resisting concrete frame is about \$241/m^2, regardless of the price of concrete members. Also, the construction cost for a 7-story moment resisting concrete frame is \$268/m^2, and for a 10-story moment-resisting concrete frame is \$288/m^2.

• The construction time for a 4-story, 7-story, and 10-story moment-resisting concrete frame is 12, 17, and 23 months, respectively for the case of Iran. Besides, the average monthly rental cost in Tehran was \$6/m^2. Therefore, the loss caused by an interruption in the building functionality could be calculated.

• The statistical value of Iranian people's lives is about \$730,660.

• The average cost for minor injuries treatment is \$205, and the average cost for major injuries treatment is \$2050. The loss caused by a disability in individuals is also calculated at about \$72,200.

• The price of building contents (the indoor equipment) is estimated at \$165/m^2, in the case of replacements with new contents.

• The proper discount rate for construction projects in Iran is 7.2%.

• The model designed with the prescriptive base shear is not optimal in terms of life cycle cost, and a factor greater than unity is required to be multiplied in this value in order to achieve the optimal design. Therefore, in order to consider LCC in structural design, the calculation method of base shear should be reconsidered.

• The optimal model of 4-story structures was obtained by a 60% increase in the base shear defined by the national seismic code. This increase in base shear to achieve the optimal model was 50% for 7-story buildings and 40% for 10-story buildings. It indicates that design based on the life cycle cost is more critical for shorter buildings.

• The reduction rate of life cycle cost in the optimal model compared to the code-based model was 16.9% for 4-story buildings, 16.1% for 7-story buildings, and 15.5% for ten-story buildings. The increase in the initial cost for all three types of structures accounted for about 2.9%.

• Investigating the secondary cost components showed that the greatest portion of secondary costs over the life cycle of the structure was comprised of the structural damage cost. Damage cost accounted for about 45% of the total secondary costs of the models.

• The Increase in concrete weight in optimal models compared to the code-based model was 21.9% for 4-story buildings, 20.8% for 7-story buildings, and 20.4% in 10-story building.

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