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TOTAL COST OF R/C BUILDINGS UNDER ALTERNATIVE EARTHQUAKE SCENARIOS

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ABSTRACT

The objective of the present paper is to investigate the influence of the design objective (which translates to a specific design strength level) on the total cost of reinforced concrete buildings. The study focuses to dual structural systems which are considered to be representative of the current construction practices. Furthermore, the role of the seismic hazard level is examined. In particular, a series of multi-storey reinforced concrete buildings are designed according to Eurocodes, using the Modal Response Spectrum Analysis method. The seismic hazard level adopted corresponds to zones I and II of the Greek territory. For each building three values of the behaviour factor q, i.e. three alternative design objectives are adopted. Thus, a total of 6 building models are designed (3 design objectives x 2 seismic hazard levels). For each model the construction cost is calculated using real cost data collected from buildings constructed in Greece during the last years. In addition, the earthquake losses are estimated by means of nonlinear dynamic analysis for three different earthquake scenarios corresponding to seismic intensities with probabilities of exceedance of 50%, 10% and 2% in 50 years. The maximum interstorey drift is used as a measure for the estimation of the relationship between the seismic response and the economic losses. The total cost of the buildings is calculated as the sum of the construction cost plus the earthquake losses. The whole investigation demonstrates that safety and economy in structural design might not be conflicting requirements.

Keywords: Design Objective; Construction Cost; Earthquake Scenarios; Economic Losses; Total Cost

1. INTRODUCTION

Performance Based Design of buildings consists of a set of provisions, rules, design criteria and methods which aim at the achievement of a predefined design objective, i.e. a predefined performance level of the structure for a specific earthquake hazard level (Avramidis 2006). The lower performance objectives (Life Safety or Collapse Prevention for the specified earthquake hazard level) are based on the design philosophy according to which in the case of strong earthquakes the utilization of the available ductility of the structures is desirable in order to absorb energy and withstand the seismic excitation without collapse. Thus, the design seismic demands are reduced and the structure is expected to undergo extensive inelastic deformations under the design earthquake. At the same time a reduction of the construction cost is achieved. It is obvious that this design philosophy implies the occurrence of extensive damage of both structural and nonstructural components in the case of a strong earthquake similar to the design earthquake. As a consequence high economic losses are expected, while the structure may remain out of service for much time. Slight damage may occur even for lower intensity earthquakes. Furthermore, in the case of a seismic excitation stronger than the design earthquake, non-repairable damage and even the global collapse of the structure cannot be precluded. Obviously, this is not consistent with the typical societal position toward building safety, which expects both governing bodies and the engineering community to preserve life safety in the design of structures against earthquakes. On the other hand, the higher performance objectives aim to provide an increased level of safety and resilience but at the same time lead to an increase in the construction cost.

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Ideally, the structure owner, after being informed by the designer, should specify the design objective taking into account both economy and safety requirements. Unfortunately, the vast majority of the building owners and occupants are not aware of the current design philosophy as well as of the possible implications of a strong ground motion on their properties. Thus, they are not involved in the definition of the design objective and the engineers usually adopt the minimum performance level prescribed in codes (which translates to the selection of the maximum permitted value of the behaviour factor q_{max}), in order to reduce the construction cost of the building. However, relevant investigations indicate that the resulting savings are not significant. Furthermore, a strong earthquake during the lifetime of the building may cause economic losses that exceed the aforementioned savings. Thus, it is doubtful whether the selection of a lower design objective is more economical in the long run. Obviously, in order to respond to this question a thorough estimation of the eventual economic losses is necessary.

In the literature one can find a large number of studies dealing with this issue. All relevant methodologies can be classified either as regional or as building-specific procedures (Aslani and Miranda 2005). Regional loss estimation procedures [e.g. (Rossetto and Elnashai 2003) (Dolce et al. 2006) (Dimitrakopoulos and Kappos 2008) (Panagopoulos et al. 2008)] aim at the estimation of economic losses for a large number of buildings within a geographical region and are used by the authorities for the development of plans against strong earthquakes. On the other hand, the building-specific procedures [e.g. (Lagaros et al. 2006) (Ramirez et al. 2012) (Liu et al. 2004) (Wen 2001) (Takahashi and Shiohara 2004) (Yang et al. 2009) (FEMA 2012) (Zareian and Krawinkler 2012) (Welch et al. 2014) (Sullivan et al. 2014)] are focused to individual buildings and can assist the owners and designers to specify the design objective of a building to be constructed (or retrofitted). According to the latter methodologies the economic losses due to an earthquake (damage of structural and non-structural components, loss of contents, downtime etc.) are expressed through a response quantity such as the maximum interstorey drift, the maximum floor acceleration or various damage indices proposed in the literature. Hence, given the seismic hazard level of a specific region, the whole procedure consists of the estimation of the selected response quantity which translates to economic losses.

Some researchers used building-specific methodologies in order to investigate the influence of the design strength level on the total cost of buildings, which comprises the construction cost as well as the eventual losses due to earthquakes. For example, Lagaros et al. (2006) compared the construction and the total cost of a reinforced concrete frame building designed for different values of the behaviour factor q ranging between 1 and 6. The total cost was estimated using a probabilistic approach with the aid of pushover analysis. The study revealed that adopting a low value of q does not lead to significant increase of the construction cost, while is more economical in long term. Ramirez et al. (2012) examined the expected cost of repairing earthquake damage in a set of 30 archetype reinforced concrete frame buildings designed according to modern codes. They demonstrated, inter alia, that the expected economic losses in the case of a design basis earthquake (for a structure located in California) are on average about 32% of the building replacement cost. Furthermore, they investigated the influence of the behaviour factor used in the design and they concluded that the adoption of a value $q = q_{max}/2$ (q_{max} the maximum permitted value by the codes) leads to a 17% degrease in expected losses. Liu et al. (2004) proposed a multiobjective genetic algorithm for design optimization of steel frame buildings. The application of the algorithm to a planar frame has shown that the traditional code-compliant design might not be the most desirable solution from an economical viewpoint due to the significant seismic damage cost.

The objective of the present paper is to investigate the influence of the design objective (which translates to a specific design strength level) on the total cost of reinforced concrete buildings. The study focuses to dual structural systems which are considered to be representative of the current construction practices. Furthermore, the role of the seismic hazard level is examined. In particular, a series of multi-storey reinforced concrete buildings are designed according to Eurocodes, using the Modal Response Spectrum Analysis method. The seismic hazard level adopted corresponds to zones I and II of the Greek territory. For each building three values of the behaviour factor q, i.e. three alternative design objectives are adopted. Thus, a total of 6 building models are designed (3 design objectives x 2 seismic hazard levels). For each model the construction cost is calculated using real cost data collected from buildings constructed in Greece during the last years. In addition, the earthquake losses are estimated by means of nonlinear dynamic analysis for three different earthquake scenarios corresponding to seismic intensities with probabilities of exceedance of 50%, 10% and 2% in 50 years. The maximum interstorey drift is used as a measure for the estimation of the relationship between the seismic response and the economic losses. The total cost of the buildings is calculated as the sum of the construction cost plus the earthquake losses. The whole investigation demonstrates that safety and economy in structural design might not be conflicting requirements.

2. STRUCTURAL MODELING AND DESIGN

In the framework of the present study, a series of typical 5-storey reinforced concrete dual wall-equivalent systems are designed according to Eurocodes 2 and 8 (European Committee for Standardization 2002) (European Committee for Standardization 2004). All storey heights are 3 m. The floor plan of the analyzed buildings is shown in Figure 1. All buildings are regular in plan and in elevation and are analyzed applying the Modal Response Spectrum Analysis method (Eurocode 8, Part 1, Section 4.3.3.3). Three alternative values of the behaviour factor q are taken into account: q_{max}, $q_{max}/2$ and 1. These values correspond to the three design objectives according to the full and partial seismic protection concept proposed by Anastassiadis et al. (2000). q_{max} is derived from the relevant provisions of Eurocode 8 (Part 1, Section 5.2.2.2). The specific values of the behaviour factor used are tabulated in Table 1. It should be stated that all buildings regardless of the q value are designed to meet the Ductility Class High requirements and the capacity design provisions. The seismic hazard level adopted corresponds to zones I and II of the Greek territory possessing Peak Ground Accelerations equal to 0.16g and 0.24g respectively with a probability of exceedance of 10% in 50 years. Totally, 6 building models are developed (3 design objectives x 2 seismic hazard levels).

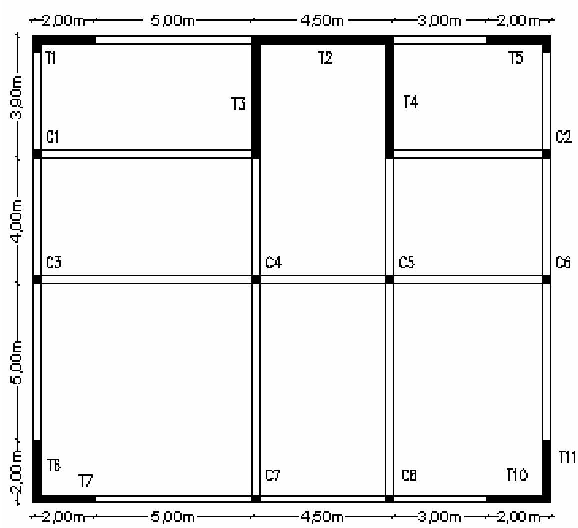

Figure 1. Floor plan of the analyzed buildings

Table 1. Behaviour factor values.

q=1	**q=q_{max}/2**	**q=q_{max}**
1	2.7	5.4

The structural analysis and the detailing of the cross sections are conducted with the aid of appropriate software widely used by engineering practitioners in Greece. The concrete is of class C20/25 (f_{ck} = 20 MPa) and the reinforcement steel bars B500C (f_{yk} = 500 MPa) according to the Greek standards. The slab thickness is equal to 15 cm. In addition to the self weight distributed dead and live loads equal to 1.5 kN/m^2 and 2.0 kN/m^2 respectively are considered. The initially chosen (minimum) height of beams

is 50 cm, while their minimum thickness is 20 cm. The dead load of masonry infill is considered equal to 9.0 kN/m for the beams lying on the perimeter and equal to 5.25 kN/m for the others. The columns' cross sections are square shaped with minimum dimension of 30 cm. Finally, the minimum thickness of walls is 25 cm and the minimum length 4.50 m (T2), 3.90 m (T3, T4) or 2.00 m (T1 and T5-T11). When the cross section of a component is not adequate to comply with the code provisions, one or both of its dimensions are successively increased using a 5 cm increment, except the length of the walls where a 10 cm increment is used.
The selected minimum dimensions correspond to minimum dimensions of structural components usually constructed in current practice in Greece. It is obvious that some components, especially beams, could meet the codes' requirements even with smaller cross section dimensions, i.e. the examined buildings, mainly those designed for the lower design objective (q_{max}), have overstrength. As a consequence the construction cost of these buildings may be overestimated with regard to an ideal building with as small as possible cross section dimensions. However, the main aim of the present study is to compare the cost for higher design objectives to the cost of real buildings which almost always are designed for q_{max} and obviously possess an amount of overstrength. Thus, the adoption of smaller cross sections dimensions would not be representative of the current construction practice and would not permit the derivation of concrete and reliable conclusions.

3. NONLINEAR ANALYSIS

3.1 Earthquake Scenarios

All the 6 buildings are analyzed by means of nonlinear dynamic analysis using four artificial accelerograms developed by the Greek Institute of Engineering Seismology and Earthquake Engineering and considered as representative of the seismic hazard of the Greek territory, given that their acceleration response spectra fit with the design spectrum of the Hellenic Seismic Code (EPPO 2003) for soil type B. Each accelerogram is scaled by six different modification factors in order to achieve the Peak Ground Accelerations (PGAs) tabulated in Table 2. These PGAs are calculated using well established empirical formulae (Koliopoulos et al. 1998) (Theodoulidis and Papazachos 1992) and correspond to probabilities of exceedance of 50%, 10% and 2% in 50 years for seismic hazard level zones I and II. Hence, for each building three earthquake scenarios are examined (A, B, C) and three different values of total cost are estimated.

Table 2. Peak Ground Acceleration of earthquake scenarios.

Seismic Hazard Level Zone	**Earthquake Scenario (Probability of exceedance in 50 years)**		
	A (50%)	**B (10%)**	**C (2%)**
I	0.10g	0.16g	0.25g
II	0.15g	0.24g	0.37g

3.2 Analysis Process

The nonlinear dynamic analysis of the buildings is performed using the program SAP 2000 v14.0.0. The modelling of the inelastic behaviour is based on the following assumptions:

- Shear failure is precluded.
- It is expected that all buildings, including those designed for q = 1, could experience inelastic deformations concentrated at the critical sections, i.e. at the ends of the structural components (plastic hinges).

- The hysteretic behaviour is defined using an elastic-perfectly plastic model (neglecting strain hardening and loss of strength or stiffness) assuming nominal design moment capacity and the yield rotation specified in Eurocode 8 (Part 3, Annex A.3).
- The moment-axial force interaction is taken into account by appropriate interaction surface incorporated in SAP 2000.
- The damping is taken into account using Rayleigh model with damping ratio equal to 5% for the first and the fourth mode of each building.

The nonlinear dynamic analysis is performed using Newmark algorithm. For the directional combination of the seismic excitation the percentage combination rule is applied. As a consequence for each accelerogram 8 combinations are examined: X+0.3Y, X-0.3Y, -X+0.3Y, -X-0.3Y, 0.3X+Y, 0.3X-Y, -0.3X+Y and -0.3X-Y. Hence, a total of 576 analysis cases are conducted (6 buildings x 3 earthquake scenarios x 4 accelerograms x 8 combinations).

3.3 Seismic Response

In order to calculate the total cost of the buildings, a seismic response quantity which expresses the earthquake losses is necessary. In the literature, quantities such as the maximum interstorey drift (Lagaros et al. 2006) (Rossetto and Elnashai 2003) (Ramirez et al. 2012) (Liu et al. 2004) (Wen 2001) (Takahashi and Shiohara 2004), the maximum floor acceleration (Takahashi and Shiohara 2004) or various damage indices are used (Panagopoulos et al. 2008) (Takahashi and Shiohara 2004). The interstorey drift is a good measure for the damage level of structures [e.g. (ASCE 2008)] and it is considered as the most appropriate quantity for estimating earthquake losses associated with damage of structural elements (Miranda et al. 2004) as well as of deformation sensitive non-structural elements (Takahashi and Shiohara 2004). The various damage indices do not provide accurate assessment of the intermediate damage states (Sinha and Shiradhonkar 2012). Concerning the maximum floor acceleration, there is no doubt that it is an important factor for building consequences, since it is representative of the loss of contents and of the damage of some acceleration sensitive non-structural elements such as suspended ceilings. However, for the vast majority of buildings the loss of contents generally represents a small percentage of earthquake losses (e.g. 17% for hotels, 20% for offices) (Takahashi and Shiohara 2004). In addition, in most cases (for example for residential buildings) the repair cost of acceleration sensitive non-structural elements, if any, is relative small in comparison with the total earthquake losses. Hence, for the sake of simplicity, many researchers [e.g. (Lagaros et al. 2006)] avoid to calculate the floor accelerations and correlate the loss of contents and the repair cost of acceleration sensitive non-structural elements with interstorey drifts (or other response quantities). The bias in the final results that is obviously introduced is considered acceptable due to the aforementioned reasons. This simplification is adopted in the framework of the present study too and the interstorey drift is used as the unique response quantity which controls the earthquake losses.

In particular, for each building and for each earthquake scenario, a representative mean value of the maximum interstorey drifts is computed applying the following steps:

- The maximum interstorey drifts D_i of all structural elements i for each analysis case are obtained from the nonlinear dynamic analysis results.
- For each storey j and for each direction (X or Y) the mean values of all elements' drifts D_{jX} and D_{jY} are calculated. When D_{jX} or D_{jY} exceeds the limits given in section 4.2, even for only one storey, it is considered that the building has collapsed for the specific earthquake scenario. Thus the next steps can be skipped.
- For each building and for each direction (X or Y) the mean values of all storeys' drifts D_X and D_Y are calculated. The maximum D_{max} of the 16 values calculated for each accelerogram (2 directions x 8 combinations) is obtained.
- Finally, the mean value of D_{max} for all the accelerograms is determined.

The representative mean interstorey drifts for all buildings and earthquake scenarios are shown in Table 3, where each building is characterized by a string symbol. The first part of the symbol indicates the seismic hazard level zone (I or II) and the second the value of the behaviour factor used for the design.

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Table 3. Mean values of the maximum interstorey drifts (‰).

Building	Earthquake Scenario		
	A	B	C
I-q_{max}	0.84	1.29	2.12
I-q_{max}/2	0.84	1.27	1.98
I-1	0.50	0.76	1.12
II-q_{max}	1.20	2.18	3.47
II-q_{max}/2	1.05	1.84	3.06
II-1	0.49	0.75	1.09

4. ECONOMICAL ANALYSIS

4.1 Construction Cost

The construction cost of the buildings has been calculated in a previous study (Manoukas and Athanatopoulou 2014) using real cost data collected from buildings constructed in Greece during the last years. As a first step, the construction cost of buildings' structural system has been calculated based on the total quantities of materials and considering that the cost of concrete is 150.3 €/m^3 and of reinforcement steel 875.25 €/t. These prices include the costs of materials, the remuneration of workers and the social security contributions. The full construction cost (structural and non-structural elements) has been then estimated based on the fact that the construction cost of a R/C building in seismic hazard level zone I for $q = q_{max}$ is about 700 €/m^2. This value is similar to the values of 750-800 €/m^2 used in previous loss estimation studies (Lagaros et al. 2006) (Dimitrakopoulos and Kappos 2008). The results (Figure 2) demonstrate that the increase of the construction cost resulting from the adoption of $q = q_{max}/2$ instead of $q = q_{max}$ is negligible, due to the overstrength that conventional buildings typically possess. Furthermore, designing for q = 1 leads to an increase of the construction cost equal to 3% for seismic hazard level zone I and 5% for seismic hazard level zone II.

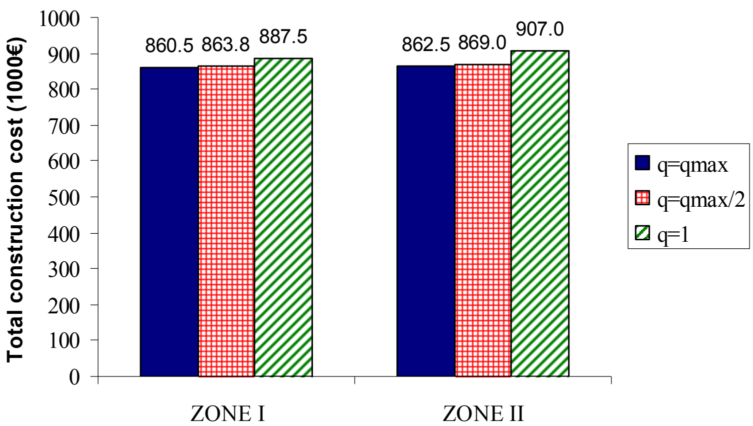

Figure 2. Construction cost of buildings

4.2 Earthquake Losses

In general, earthquake losses comprise costs for repairing the damage of structural and non-structural components, loss of contents, rental and relocation costs, general income losses, injuries and human

fatality. General income losses are significant for commercial buildings only and they are not taken into account in the present study. Additionally, the cost of injuries and human lives is neglected, because the existing methodologies for its quantification in economical terms are quite ambiguous.
The cost for repairing the damage of structural and non-structural components is expressed as a percent of the initial construction cost of each building. This percent is related to the interstorey drift according to Table 4 (for intermediate values linear interpolation is conducted). The values of the table are taken from the relevant literature (ASCE 2008) (Lagaros et al. 2006) (ATC 1985) (FEMA 1992) (Ghobarah 2004).

Table 4. Relation between earthquake damage repairing cost and interstorey drift.

Earthquake damage repairing cost (% of construction cost)	**Interstorey drift (‰)**
0	0
0.5	0.67
5	1.33
20	2.67
45	6.67
80	12
100	20

Concerning the loss of contents and based on engineering judgment, it is assumed that the total value of the contents amounts to 250 €/m^2. This value corresponds to residential buildings in Greece and is equal or similar to the values used by other researchers (Lagaros et al. 2006) (Dimitrakopoulos and Kappos 2008). The loss of contents is calculated using the same percent obtained from Table 4.
Finally, the rental cost depends on the time after the earthquake that the building remains out of service. In general, the precise determination of the downtime is very difficult given that it varies depending not only on the damage level, but on economic and social factors too. This is reflected to statistical data collected from recent earthquakes (Comerio 2006) (Comerio and Blecher 2010). In the framework of the present study, it is considered that the time needed for the reconstruction of a fully collapsed building is 18 months. The downtime of each building for each earthquake scenario (in months) is calculated multiplying 18 by the percent obtained from Table 4. Then the rental cost is calculated on the basis of the realistic assumption that the rent of a typical building in Greece is about 4 €/m^2 per month. This value is increased by 25% in order to account indirectly of the relocation cost. The rental cost adopted is equal to the one used by Dimitrakopoulos and Kappos (2008), but much lower than the 7 €/m^2 per month cost used by Lagaros et al. (2006). This difference reflects the significant reduction of rents in Greece during the last years due to the economic crisis.
The earthquake losses (Figures 3 and 4), expressed as percent of the construction cost of each building, range between 0.5% and 6.1% for earthquake scenario A, between 1.5% and 21.5% for earthquake scenario B and between 4.9% and 37.1% for earthquake scenario C. In most cases there is no remarkable difference between buildings designed for $q = q_{max}$ and those designed for $q = q_{max}/2$. However, designing for $q = 1$ (i.e. for elastic response under the design earthquake) leads to a significant reduction of losses, which remain almost constant regardless of the seismic hazard level zone. On the contrary, for the buildings with lower design strength levels, considerable differences between zones I and II occurred. In particular the losses are much higher in zone II, which means that designing with the same behaviour factor in different seismic zones leads to different level of safety. This finding is consistent to the findings of previous studies (Thuat 2014) and indicates that likely the values of q_{max} given in seismic codes should be diversified depending on the seismic hazard level zone.

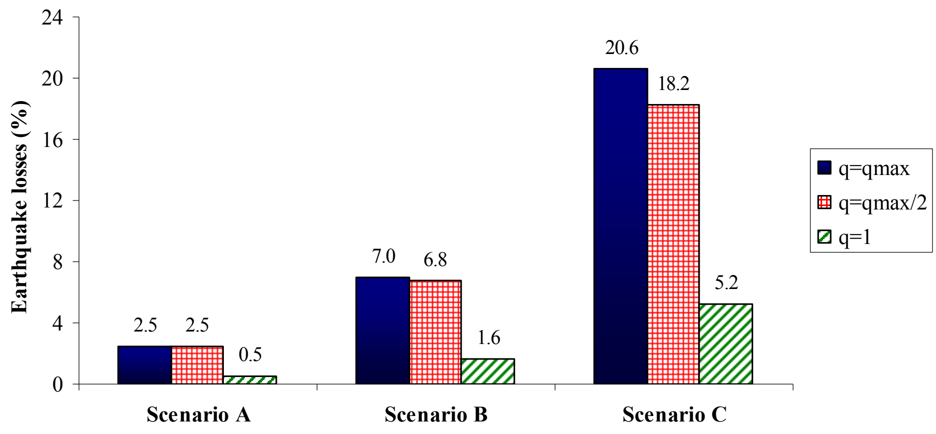

Figure 3. Earthquake losses (% of the construction cost) – seismic hazard level zone I

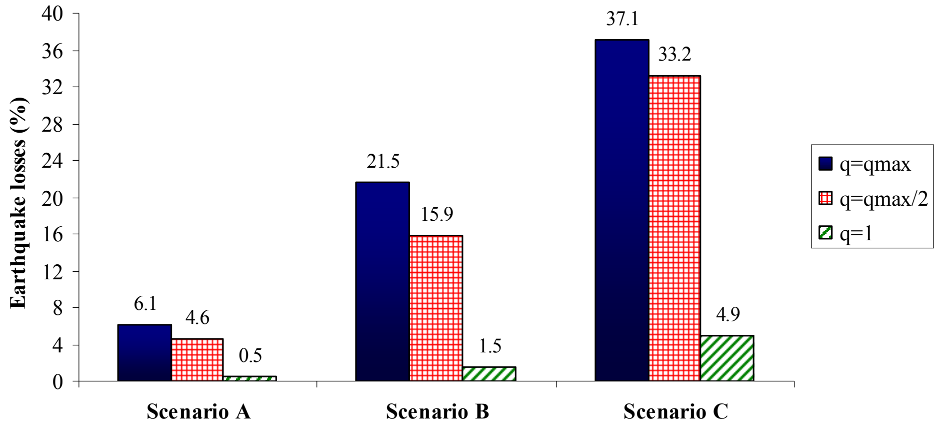

Figure 4. Earthquake losses (% of the construction cost) – seismic hazard level zone II

4.3 Total Cost

The total costs of the buildings normalized to the cost of the conventionally design buildings (i.e. for $q = q_{max}$) for each earthquake scenario are shown in Figures 5 and 6. It is apparent that, concerning earthquake scenario A, there is no remarkable difference in the costs between the three alternative design strength levels. However, for earthquake scenario B and especially for earthquake scenario C, a reduction of the total cost up to 20% is achieved by adopting a value of behaviour factor equal to 1. The reduction is particularly pronounced for zone II.

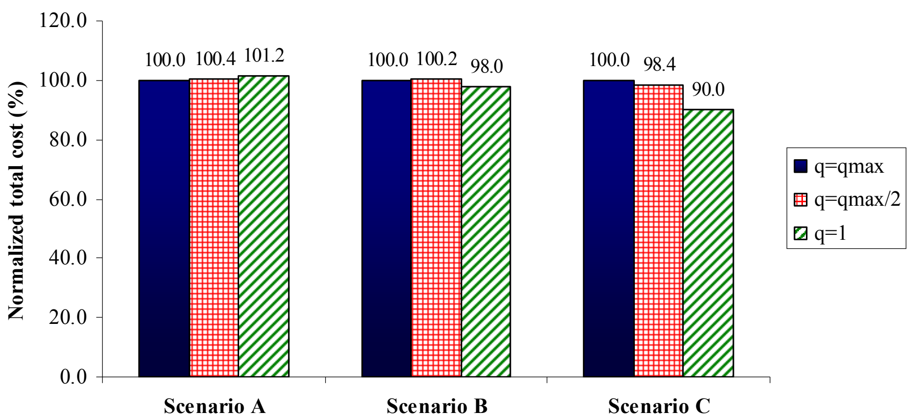

Figure 5. Normalized total cost of buildings – seismic hazard level zone I

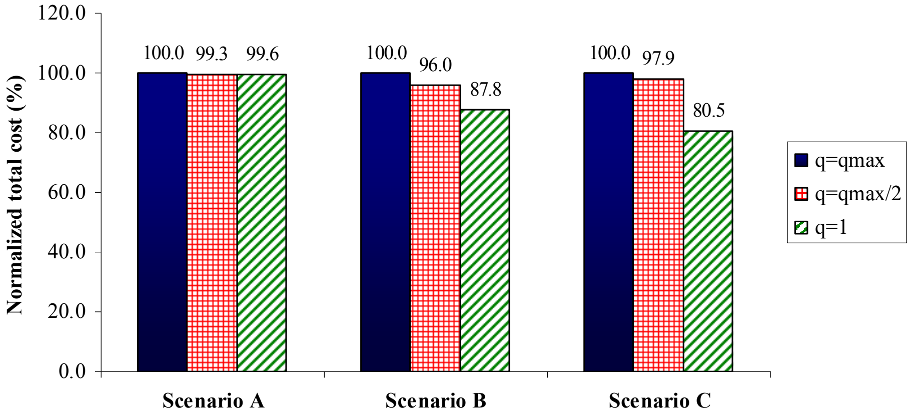

Figure 6. Normalized total cost of buildings – seismic hazard level zone II

5. CONCLUSIONS

The scope of this paper is to investigate the influence of the design objective (which translates to a specific design strength level) on the total cost of dual reinforced concrete systems. For this purpose a parametric study is conducted comprising the design of a series of 5-storey reinforced concrete buildings for alternative design objectives and seismic action levels, as well as their nonlinear dynamic analysis for three earthquake scenarios. The buildings are designed to meet the Ductility Class High requirements of codes, given that all structures, regardless of the design strength level, should possess an adequate amount of ductility in order to withstand without collapse seismic excitations even stronger than the design earthquake. The main conclusions derived are as follows:

- The increase of the construction cost resulting from design for $q = q_{max}/2$ instead of $q = q_{max}$ is negligible, due to the overstrength that is commonly associated with the conventional buildings (i.e. buildings designed for $q = q_{max}$ and constructed according to the current engineering practice).
- In the case of design for elastic response under the design earthquake ($q = 1$), the additional construction cost is not prohibitive.
- The earthquake losses of conventionally designed buildings (i.e. for $q = q_{max}$) are much higher in seismic hazard level zone II in relevance to zone I. In order to achieve a uniform level of safety regardless of the seismic hazard level zone, a revision of code provisions regarding the value of q_{max} should be examined.
- In the case of a moderate seismic excitation (earthquake scenario A), the total cost does not depend on the design strength level. However, in the case of the design earthquake (scenario B) and especially in the case of an even stronger earthquake (scenario C) significant reduction of the earthquake losses as well as of the total cost can be achieved by adopting a behaviour factor value equal to 1.

Conclusively, the findings of the present study indicate that designing for elastic response against the design earthquake and at the same time keeping a high level of ductility is both the safest and the most economical in long term option in the case of strong seismic excitations. However, in order to generalize this conclusion further investigations are required, comprising applications to a large variety of buildings, thorough analysis of the seismic hazard of specific regions and consideration of various economic and social aspects.

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