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CRITERIA FOR SEISMIC RISK REDUCTION OF EARTHQUAKE RESISTANT BUILDINGS

Jakim T. PETROVSKI[1]

SUMMARY

Most of the existing seismic design codes are based on the empirical knowledge accumulated through systematic earthquake damage data collection and their analysis. Required levels of protection and seismic design forces gradually are increased after each series of catastrophic earthquakes particularly in developed countries. Many efforts have been made through experimental and analytical studies to improve detailing and to increase inelastic capacity of buildings and structures to resist earthquake ground motions with acceptable damage levels. The general believe was that empirically developed seismic design codes contain performance objectives, but usually in a descriptive form that cannot be quantified and that explicit code design for life safety provides adequate damage protection.
The main source of damage to structural systems and in particular nonstructural elements are deformations and interstory drifts imposed by earthquake ground motions. Therefore, to control damage, it is necessary to control deformation and particularly to control interstory drift. Thus, achievement of reliable and efficient earthquake resistant design of buildings and structures requires satisfaction not only of the criteria for strength but also the criteria for deformation and reparability which are directly inter-related. Although, there have been proposals to base seismic design on only lateral stiffness, i.e. only controlling the story drift, a practical method of this type of design has been recently developed using damage control criteria based on acceptable level of direct economic losses.
Damage control criteria based on acceptable level of direct economic losses is formulated for earthquake resistant structural systems and non-structural elements, considering damage cost of both groups of elements as directly dependant of the structural response mechanism and story drifts to selected earthquake ground motions and their intensities. Two basic categories of ordinary and essential class of buildings are considered. For ordinary buildings governing criteria is damage control defined with the range of maximum story drift for Planning Scale Earthquake scenario, based on building damage data in the past earthquakes, experimental studies and calibration with numerous performance analyses. For essential class of buildings, like schools and health buildings, buildings with high occupancy rate, governing criteria is serviceability limit state defined with the range of maximum story drift for seismic hazard level of Maximum Considered Earthquake scenario, considering them to remain in safe and operational conditions after earthquake disaster. Established criteria is demonstrated with the presented results of seismic performance analysis and damage cost evaluation of the 19 structural systems of essential class of low and high rise buildings and 6 structural systems of ordinary non and earthquake resistant buildings.

[1] Professor, Institute of Earthquake Engineering and Engineering Seismology,
University ”Cyril and Methodius”, Skopje, Republic of Macedonia

INTRODUCTION

Developed empirical performance criteria have been used in many countries for estimation of physical, functional and economic losses, planning for reconstruction of earthquake stricken regions, or simulation of expected earthquake losses for different level earthquake hazard scenarios in prioritization of upgrading projects dominantly of low earthquake resistant buildings and structures, disaster preparedness planning and planning for seismic risk reduction. With rapid increase of strong motion instrumentation of buildings and structures in the past 30 years, and improvement of understanding of nonlinear behavior of different structural systems and dominant nonstructural components of buildings based on experimental studies as well as development of rational software for analysis, demand for specific quantification of the performance evaluation of existing buildings and structures has been opened by building owners and governmental officials. To fulfill this demand for establishment and implementation of quantified performance criteria, significant efforts have been made by many researches and professionals, and opportunities are realistic to define various limit states and associated performance criteria, based on the inelastic response analysis of structural systems and dominant nonstructural components for buildings and structures, verified by using real time digital strong motion recording systems for individual structures, or assessment of experienced performance level of the group of important structures and extended urban area exposed to the future earthquakes.

Most of the existing seismic design codes are based on the empirical knowledge accumulated through systematic earthquake damage data collection and their analysis. Required levels of protection and seismic design forces gradually increased after each series of catastrophic earthquakes particularly in developed countries. Many efforts have been made through experimental and analytical studies to improve detailing and to increase inelastic capacity of buildings and structures to resist earthquake ground motions with acceptable damage levels. The general believe was that empirically developed seismic design codes contain performance objectives, but usually in a descriptive form that cannot be quantified and that explicit code design for life safety provides adequate damage protection. Because of its simplicity the present design practice based on the empirically developed seismic design codes, has served the profession well, but as structures become more complex and new and innovative structural systems are being developed, a more rational method of designing for specified levels of performance and performance evaluation has become necessary.

The nonlinear dynamic response analysis methodology is based on the premise that damage and ultimately collapse are caused by excessive deformations. The design objective is to provide a structure with sufficient strength, stiffness, and ductility such that the deformation demands imposed by design earthquakes are less than the deformations associated with acceptable damage at the various limit states at which performance is to be evaluated. Strength by itself is considered as a critical issue only for structural damage control at serviceability limit states and for individual elements that fail in a brittle mode and must be protected from excessive overloads at the collapse prevention level. The overriding consideration in this approach is that every step is based on fundamental physical concepts that make the design process equally applicable to the seismic evaluation of existing structures and seismic design of new structures, using conventional structural systems as well as new structural systems, materials and innovative energy dissipation or base isolation systems. The methodology employs a multi-level design approach, concerned with the seismic performance levels identified before. The designs may be performed in parallel or sequentially, depending on the ability to recognize the dominance of one level over the other. Very often, serviceability design controls the elastic strength and stiffness of the structure, and design for collapse prevention can focus on providing sufficient deformation capacity and reserve strength in the inelastic range of structural behavior (2, 3, 7, 12, 14, 15, 17).

The growing concern over direct, functional and indirect earthquake losses and the difficulty in repairing post-yield damage of structural components indicates the need for more attention to be given to control of damage and reparability at the design stage of the buildings and structures. The control of damage will also help to improve life safety, which is traditional fundamental criteria. The main source of damage to structural systems and in particular nonstructural elements are deformations and interstory drifts imposed by earthquake ground motions. Therefore, to control damage, it is necessary to control deformation and particularly to control interstory drift. Thus, achievement of reliable and efficient earthquake resistant design of buildings and structures requires satisfaction not only of the criteria for strength but also the criteria for deformation and reparability which are directly interrelated and may be defined with recently established damage control level as one of limit states for earthquake resistant design (10).

Present practice emphasizes the use of strength as the primary criterion for earthquake resistant design of structures. While seismic design based on shear strength could be justified where serviceability controls, it cannot be accepted in cases where the design is controlled by the ultimate limit state (collapse prevention) where plastic deformation is accepted. At safety limit state, base shear is intensive to variation of deformation and, therefore, to damage. Although there have been some proposals to base seismic design on only lateral stiffness, i.e. on only controlling the story drift, a practical method of this type of design has been recently developed using damage control criteria based on established criteria for acceptable level of direct economic losses (10). This rational approach is one that not only recognizes the importance of strength and stiffness (control of deformation), but also recognizes that while these two factors are strongly interrelated in the case of elastic response, they are less strongly interrelated in the case of inelastic response. To control inelastic deformation, however, it is necessary to provide the structure with a minimum yielding strength. Therefore, to achieve an efficient earthquake resistant design there is a need to consider two requirements simultaneously: the strength, based on the rational use of hysteretic energy and the deformation, based on the limitation of story drift (Fig. 1).

EARTHQUAKE DAMAGE AND LOSS CONTROL CRITERIA

For the purpose of seismic performance evaluation and development of damage cost functions as one of the most significant tools for analysis of earthquake losses and seismic risk in regional and urban development planning as well as seismic verification of earthquake resistant design of individual buildings, economic loss functions for earthquake resistant structural systems in relation to story drift, safety level and damage category have been developed (Fig. 2). Economic loss functions are calibrated with large number of developed empirical and analytical damage cost functions based on performance analysis of the selected representative structural systems of buildings. Earthquake damage and loss control criteria based on acceptable level of direct economic losses is formulated simultaneously for earthquake resistant structural systems and non-structural elements consisting damage cost of both groups of elements, as directly dependant of the structural response mechanism and developed story drifts to selected representative earthquake ground motions, with predefined criteria of their intensities for two basic categories of ordinary and essential class of buildings and their facilities (12, 14, 15).

For ordinary buildings governing criteria is damage control defined with maximum story drift limited to Δ=1.35%, based on buildings damage data in the past earthquakes, experimental studies and calibration with numerous performance analysis for the level of Planning Scale Earthquake Scenario (PSE, 0.35 g). For essential class of buildings like school and health buildings, buildings with high occupancy rate (high rise buildings, theatres, cinemas, sports and other facilities), governing criteria is serviceability limit state defined with maximum story drift Δ =0.3 to 0.6% for seismic hazard level defined as Maximum Consider Earthquake Scenario (MCE, 0.455 g).

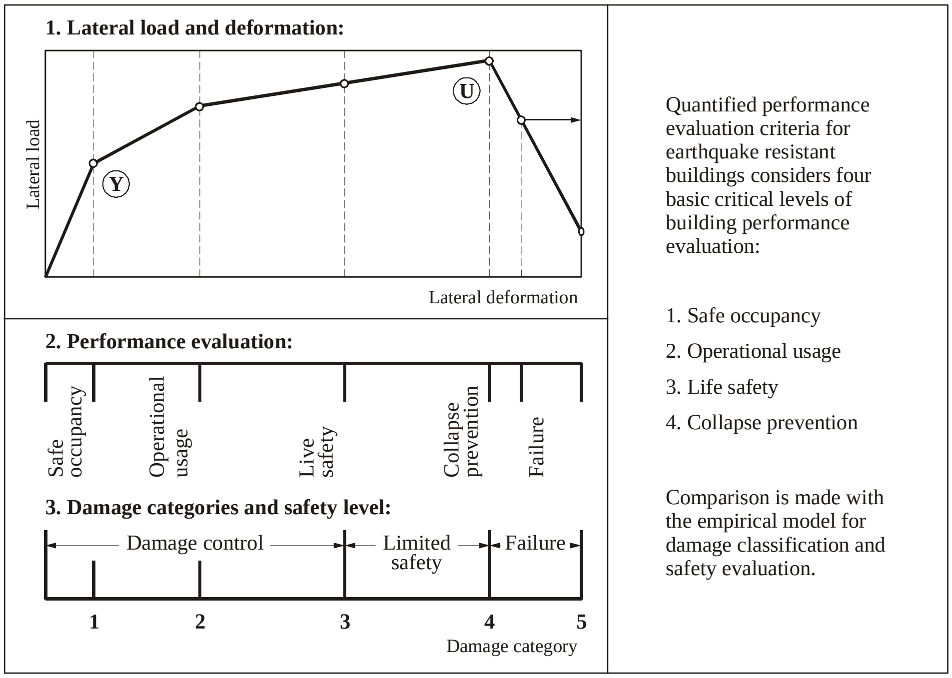

Fig.1. Performance evaluation criteria for earthquake resistant buildings

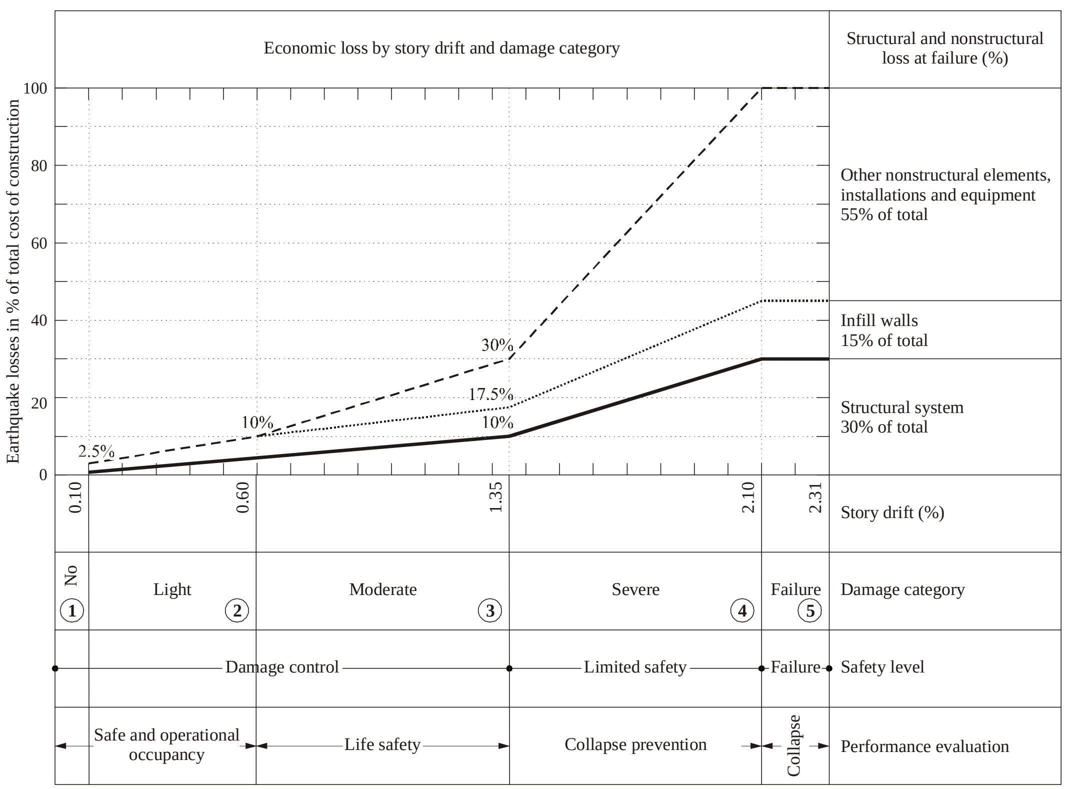

Fig. 2. Economic loss functions for earthquake resistant structural systems and nonstructural components in relation with story drift, damage category and safety level (after Petrovski, J. T., 1992), (10)

The following three critical levels, based on performance evaluation have been established as criteria for damage control and collapse prevention for ordinary buildings and safe and operational occupancy for essential buildings (Fig. 1 and 2): **Safe and operational occupancy:** Story drift is limited to 0.6% and damage cost to 10% of the entire cost of earthquake resistant building including structural and nonstructural damage cost; **Life safety damage control level:** Story drift is limited to 1.35% and damage cost to 30% of the entire cost of the earthquake resistant building; **Collapse prevention:** Story drift is limited in the range of 1.35% to 2.1% and damage cost of the building is larger than 30% of the entire cost of earthquake resistant building.

Earthquake ground motion intensities and time histories need to be defined from probabilistic hazard maps and site specific studies for each of considered critical levels and building class as formulated below: Life safety damage control level and collapse prevention of ordinary buildings should be performed for the level of seismic hazard defined as Planning Scale Earthquake Scenario (PSE) with 10% probability of exceedence in 50 years. For essential facilities like school and health buildings, buildings with high occupancy rate (high rise buildings, theatres, cinema, sport and other facilities), the buildings should remain in operational conditions at the level of story drift in the range of 0.3 to 0.6% for seismic hazard defined as Maximum Considered Earthquake Scenario (MCE) with 5% probability of exceedence in 50 years. Earthquake time histories for performance analysis should be defined on the basis of seismic source characteristics and local soil conditions of the urban area or specific site.

SEISMIC PERFORMANCE AND DAMAGE COST EVALUATION

Procedure implemented for development of earthquake damage cost functions is based on the seismic performance analysis and defined direct economic loss functions for structural systems and nonstructural components (Fig. 2). For seismic performance analysis representative existing and recommended earthquake resistant structural systems of essential class of buildings and ordinary buildings have been selected. Seismic performance analyses are executed through nonlinear dynamic time history response analysis of 19 reinforced concrete structural systems of essential class of buildings and 6 reinforced concrete and masonry structural systems of ordinary buildings, summarized with base shear strength capacity, deformation characteristics and maximum story drifts in Table 1 and 2. Nonlinear time history dynamic response analyses have been performed; using computer programs DRAIN-2DX (16) and IDARC 2D, Version 4.0 (18), or specially developed software package DIAG (5).
Intensities of earthquake ground motions for four levels determined by seismic hazard analysis and seismic microzoning of the Metropolitan area and the city of Rasht in Northern Iran, for planning of seismic risk reduction (11). These four levels are determined by maximum expected ground acceleration of moderate hazard of frequent scale earthquake (FSE, 0.164 and 0.245g), high hazard of planning scale earthquake (PSE, 0.35g) and very high hazard of maximum considered earthquake scenario (MCE, 0.455g).

Selected earthquake time histories of Abbar and Lahijan records of June 20, 1990 Manjil Earthquake are covering dominantly firm and soft soil conditions in the region. These two earthquake time histories combined with El Centro 1940 record, are used to develop most probable envelopes of damage cost functions and representative quantities obtained by seismic performance analysis of the selected types of structural systems (Table 1 and 2).

Damage cost functions of essential class of buildings

Using the results of nonlinear dynamic response analyses of considered representative structural systems and developed economic loss functions, envelope earthquake damage cost functions have been developed (Fig. 3 and 4) and presented separately as damage cost functions for structural systems and total damage cost functions, including structural system and nonstructural components, for all three earthquake time histories. An example of envelope earthquake damage cost functions of reinforced concrete moment resisting frame hospital building is presented in Fig. 3, and in Fig. 4 envelope earthquake damage cost functions of reinforced concrete moment resisting frame with shear walls of the same hospital building. Total damage cost in the case of moment resisting frame is about 25% of the construction cost for PGA=45%g and does not satisfy criteria to be lower than 10% for essential class of buildings exposed to Maximum Considered Earthquake Scenario (Fig. 3, Table 1). In the case of the reinforced concrete moment resisting frame with shear walls total envelope damage cost for PGA=45%g is 14.2% and is closer to satisfy criteria of damage cost lower than 10% of construction cost with improvement of shear walls capacity (Fig. 4, Table 1).

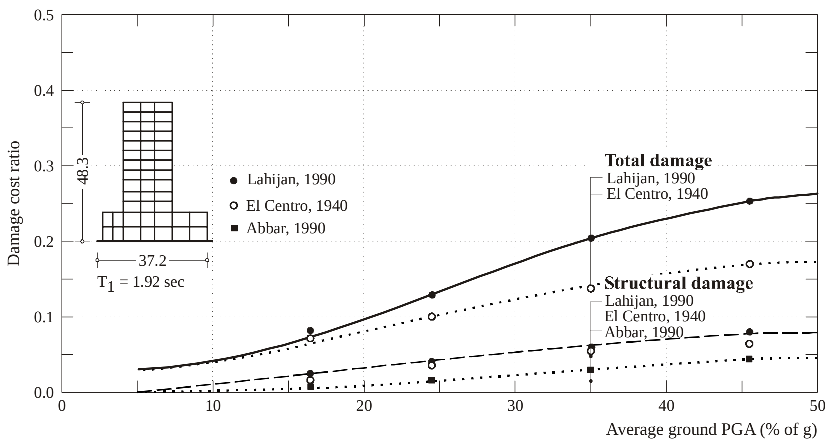

Fig. 3. Envelope earthquake damage cost functions of reinforced concrete thirteen story moment resisting frame hospital building

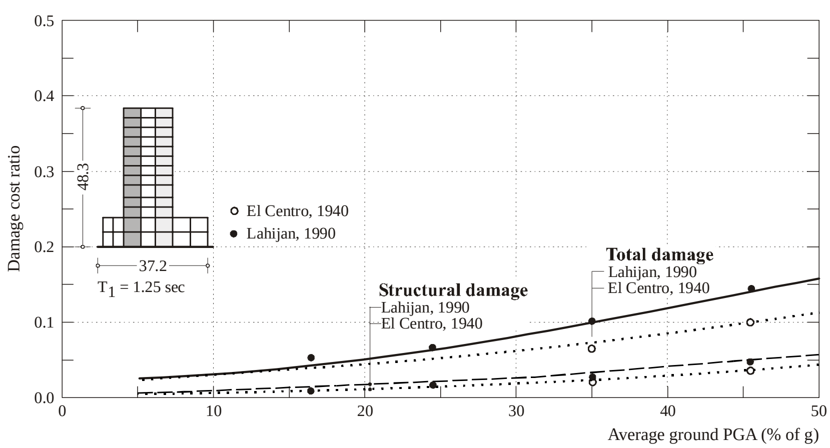

Fig. 4. Envelope earthquake damage cost functions of reinforced concrete thirteen story moment resisting frame with shear wall hospital building

Table 1. Seismic performance evaluation and expected damage cost for earthquake resistant essential buildings

Essential public buildings and structural system	Vibration period T (sec)	Performance evaluation			Envelope damage cost ratio		Satisfied criteria
		Base shear strength c_y	Maximum story drift Δ (%)	Story level	Structural (%)	Total (%)	
1. Model school building							
Two story school building:							
1.1. Unreinforced masonry in cement mortar grade M5	0.13	0.57	0.24	1	59.40	59.40	No
1.2. Confined masonry with plain brick infill walls	0.12	0.37	0.60	1	0.92	10.53	Yes
1.3. Moment resisting frame with hollow block infill walls	0.33	0.40	1.09	1	8.21	23.19	Yes with imp.
1.4. Moment resisting frame with shear walls	0.22	0.52	0.63	2	4.83	11.13	Yes with imp.
Four story school building:							
1.5. Unreinforced masonry in cement mortar grade M5	0.225	0.38	0.37	1	98.40	98.40	No
1.6. Confined masonry with plain brick infill walls	0.38	0.24	1.43	2	12.26	20.62	Yes with imp.
1.7. Moment resisting frame with hollow block infill walls	0.65	0.18	1.42	2	9.29	28.80	Yes with imp.
1.8. Moment resisting frame with shear walls and hollow block infill walls	0.44	0.23	1.04	3	7.71	21.29	Yes with imp.
2. Model health building							
Two story health building:							
2.1. Confined masonry with plain brick infill walls	0.10	0.52	0.85	1	6.24	8.65	Yes
2.2. Moment resisting frame with hollow block infill walls	0.33	0.35	1.46	1	3.60	12.90	Yes with imp.
2.3. Moment resisting frame with shear walls and hollow block infill walls	0.06	0.67	0.02	2	0.00	0.44	Yes
Four story health building:							
2.4. Confined masonry with plain brick infill walls	0.25	0.47	2.36	1	10.00	18.50	Yes with imp.
2.5. Moment resisting frame with hollow block infill walls	0.62	0.20	1.32	2	8.08	24.07	Yes with imp.
2.6. Moment resisting frame with shear walls and hollow block infill walls	0.18	0.89	0.17	4	0.00	3.87	Yes
3. High rise hospital building							
3.1. Moment resisting frame	1.92	0.13	1.11	11	7.84	25.31	No
3.2. Moment resisting frame with shear walls	1.25	0.21	0.72	12, 13	4.81	14.18	Yes with imp.
4. Model high rise office and residential buildings							
4.1. Eight story moment resisting frame with shear walls	0.56	0.52	1.11	7	6.31	15.99	Yes with imp.
4.2. Twelve story moment resisting frame with shear walls	0.99	0.32	0.76	10-12	3.50	9.16	Yes with imp.
4.3. Sixteen story moment resisting frame with shear walls	1.47	0.19	0.86	13, 14	4.53	10.79	Yes with imp.

Criteria for seismic performance evaluation: Considering schools, hospitals and other health buildings, fire stations, as well as high occupancy buildings as: high rise buildings, sport, cinema, theatre and other, as essential class of buildings, important for evacuation, rescue and relief operations, governing criteria for performance evaluation is seismic hazard defined as Maximum Considered Earthquake Scenario with 5% probability of exceedence in 50 years. For this hazard level, essential buildings should remain in safe and operational conditions, with limited interstory drift in the range Δ=0.3 to 0.6%, and damage cost should be lower than 10% of the total cost of construction of earthquake resistant buildings.

Damage cost functions of ordinary buildings

Damage cost functions for ordinary low rise residential masonry buildings with only horizontal tie beams at each floor level, considered as non-earthquake resistant buildings (Fig. 5 and 6) and confined masonry buildings with horizontal and vertical tie beams (Fig. 5 and 7) have been developed using the results of nonlinear dynamic response analysis and developed economic loss functions for masonry structural systems and presented in Fig. 5 as an example for two story masonry building. It is evident that only confined masonry could satisfy the criteria for earthquake resistance of ordinary buildings (Fig. 5 and Table 2).

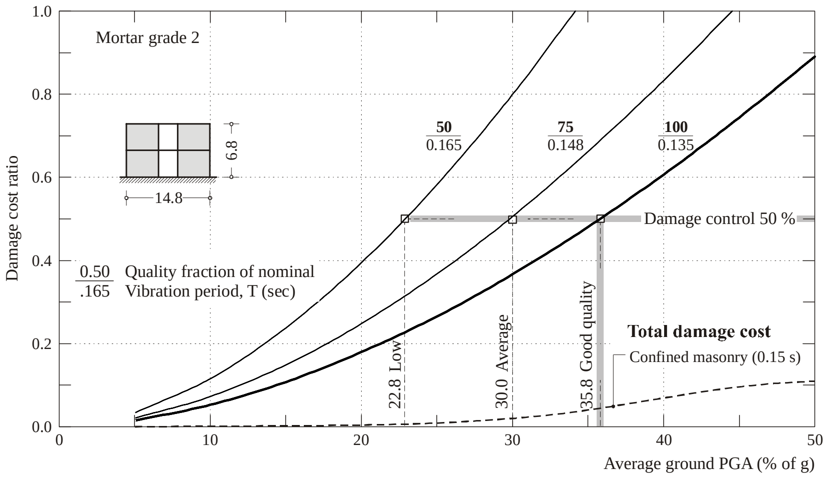

Fig.5 Envelope earthquake damage cost functions of two story residential buildings constructed in unreinforced masonry mortar grade M2, and confined masonry structural system

Table 2. Seismic performance evaluation and expected damage cost for non and earthquake resistant residential buildings

Residential buildings and structural system	Vibration period T (sec)	Performance evaluation			Envelope damage cost ratio		Satisfied criteria
		Base shear strength c_y	Maximum story drift Δ (%)	Story level	Structural (%)	Total (%)	
1. Five story reinforced concrete buildings							
1.1. Moment resisting frame with hollow brick infill	0.85	0.19	1.18	4	4.69	12.29	Yes
1.2. Moment resisting frame with plain brick infill	0.67	0.30	0.95	3	6.38	10.34	Yes
1.3. Moment resisting frame with shear walls and hollow brick infill	0.47	0.39	0.59	5	2.62	5.49	Yes
2. Low rise residential buildings							
Two story residential buildings:							
2.1. Unreinforced masonry in cement mortar M2 with horizontal tie beams	0.135	0.35	2.09	1	50.00	50.00	No
2.2. Unreinforced masonry in cement mortar M5 with horizontal tie beams	0.111	0.40	1.85	1	50.00	50.00	No
Four story residential buildings:							
2.3. Unreinforced masonry in cement mortar M5 with horizontal tie beams	0.202	0.26	2.65	1	64.00	64.00	No
2.4. Unreinforced masonry in cement mortar M8 with horizontal tie beams	0.179	0.28	2.18	1	40.00	40.00	No
2.5. Confined masonry in cement mortar grade M2	0.31	0.34	1.23	1	4.07	6.71	Yes

Criteria for seismic performance evaluation: Considering residential buildings as ordinary class of buildings, governing criteria for performance evaluation is seismic hazard defined as Planning Scale Earthquake Scenario (PSE, 0.35g) with 10% probability of exceedence in 50 years. For hazard level of Planning Scale Earthquake Scenario, as defined by economic loss functions, residential buildings should be under damage control with limited interstory drift, $\Delta \leq 1.35\%$. For this limited level of interstory drift $\Delta = 1.35\%$, damage cost should be lower than 30% of the total cost of construction of earthquake resistant buildings.

Fig.6 Collapse of the corner of a two-storey unreinforced brick masonry building with horizontal tie beams only at the second floor (after Razani, R., 1998)

The first floor does not have tie - beams. There are no tie - columns. The bearing walls and first floor collapsed at the corner. The bearing walls of the first floor received diagonal shear cracks. The front bearing wall of the upper storey became separated from the upper tie - beam and is on the verge of falling inside. The roof tie - beams saved the roof from collapse and disintegration even though the corner bearing walls fell down. The existence of a tie - column at the corner and a tie - beam at the first floor could have saved this building from collapse. The existence of a small opening in the walls has been beneficial.

Fig.7 An example of new housing complex in suburbs of the city of Rasht of low rise confined masonry buildings without damage (after Petrovski, J.T., 1998)

Seismic performance and damage cost evaluation of essential class of buildings

Seismic performance and damage cost evaluation for 19 structural systems of essential buildings, such as: model school and health two and four story buildings; high rise hospital building and model high rise 8, 12 and 16 story buildings, is summarized based on seismic performance analysis results and developed envelope damage cost functions. Criteria required to be satisfied at serviceability limit state Δ=0.3 to 0.6% and total damage cost 10% of total construction cost for Maximum Considered Earthquake Scenario, is checked for each of considered structural systems of essential buildings. All relevant parameters, such as: base shear strength, initial vibration period, maximum story drift and story level of occurrence as well as envelope damage cost ratio of structural system and total damage in % of total construction cost, are presented in Table 1. Finally satisfaction according to both criteria: maximum story drift and total damage cost are checked and commented.

For a good conceptual design of confined masonry and moment resisting reinforced concrete frame with shear walls structural system of low rise school and hospital buildings, both criteria are satisfied or require slight improvement. Moment resisting frames with hollow block infill walls should be avoided. If these infill walls are of fired brick incorporated in the structural system, reinforced concrete moment resisting frames will satisfy both criteria. For high rise essential buildings only reinforced concrete moment resisting frame with shear walls structural system will satisfy both required criteria. For all considered buildings even with shear wall structural system slight improvement of shear wall capacity is further required.

Seismic performance and damage cost evaluation of ordinary buildings

Seismic performance and damage cost evaluation for 3 structural systems of mid rise and 5 structural systems of low rise urban residential buildings is performed based on the defined criteria of damage control at maximum interstory drift Δ = 1.35% and damage cost up to 30% of total construction cost exposed to Planning Scale Earthquake Scenario (PSE). All relevant parameters for seismic performance and damage cost evaluation for considered structural systems are summarized in Table 2. Moment resisting reinforced concrete frames with hollow brick infill will satisfy both criteria with slight improvement. Moment resisting frame with shear walls is evidently most favorable structural system. For low rise residential buildings implementing the same criteria of damage control for Planning Scale Earthquake Scenario, all two and four story unreinforced masonry buildings do not satisfy criteria of damage control at the level of 30% damage cost. Only confined masonry structural system completely satisfies both criteria and could be recommended for construction of low rise earthquake resistant residential buildings.

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