Evaluation of vulnerability and potential seismic risk level of buildings

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ABSTRACT: For evaluation of appropriate strategies for reduction of seismic risk in urban areas, theoretical vulnerability prediction of existing building structures under expected future earthquakes is one of the most essential engineering steps. However, due to the complexity of the problem, most of the existing procedures introduce large theoretical simplifications implementing in the analysis single-degree-of-freedom systems and response spectra.

This paper introduces recently developed more complex but improved concept for theoretical building vulnerability prediction which is based on inelastic earthquake response computation of the integral structure. Improvement of the fomulated structural model is achieved by consideration of specific nonlinear behaviour features of both structural, as well as nonstructural components based on experimental results from available and newly conducted experimental results. Through the development of theoretical vulnerability functions of buildings implementing the proposed concept, more reliable assessment of seismic risk in urban areas could be performed.

1 INTRODUCTION

Very high vulnerability of existing buildings has been observed during recent catastrophic earthquakes (Armenia, USSR 1989, Mexico City 1985, Montenegro, Yugoslavia 1979, Manjil Earthquake, Iran 1990, etc.). It is particularly indicative that even modern buildings have sustained serious damage including heavy structural failures and total collapse in many cases. To meet the general need for assessment and earthquake risk mitigation in urban areas, the present study introduces an integral procedure for earthquake vulnerability or damage/loss prediction of existing buildings based on development of theoretical vulnerability functions for appropriately defined expected earthquake intensity ranges.

The proposed concept for development of building vulnerability functions is based on application of experimental test data and formulated predictive model of inelastic response of the integral structure. Selected results from the conducted experimental test along with the theoretical background of the proposed analytical model for building vulnerability analysis based on previously calibrated damage criteria of structural and nonstructural components are presented and briefly discussed in the first part of this paper. To demonstrate application of the developed concept for vulnerability prediction of existing buildings and assessment of acceptable level of seismic risk, some typical results related to the recently analysed example buildings are also included and discussed in the second part.

2 BASIC CONCEPT AND PROCEDURE FOR DEVELOPMENT OF THEORETICAL VULNERABILITY FUNCTIONS

Observed heavy building damage under earthquake ground excitation generally results from intensive structural vibration dominantly in the nonlinear range. The inelastic dynamic response of the integral structure is fully controlled by specific inelastic response characteristics of all constituent not only structural, but commonly by many other existing nonstructural components.

In that respect, to provide methodology for realistic vulnerability analysis of existing buildings, the proposed concept incorporates various important steps, as follows: (1) development of analytical hysteretic models representing realistically inelastic response of different structural and nonstructural components, (2) determination of specific response-based damage criteria at the element level, (3) nonlinear analytical model formulation of the integral structure through implementation of the proposed element hysteretic models, (4) development of appropriate computational procedure for inelastic earthquake response prediction based on the formulated structural model, (5) determination of representative set of earthquake ground motions reflecting local conditions and expected seismicity, (6) computation of a series of inelastic structural responses for different earthquake intensity levels, (7) determination of representative story response relations based on available structural earthquake response statistics, (8) vulnerability evaluation

at the element level based on developed specific response-based damage criteria, (9) independent vulnerability evaluation of structural and nonstructural elements at each story level, and (10) cumulative vulnerability evaluation of the integral building based on specific loss functions for selected representative earthquake ground motions.

Implementing the presented concept, vulnerability functions for different building classes defined by building classification in respect to various significant parameters such as type of structural system, number of stories, material and construction quality, type of foundation, types of nonstructural-infill components, etc., can be developed and practically implemented for respective risk evaluation purposes.

2.1 Experimental tests for model and damage criteria evaluation

Most commonly, in formulation of the analytical model for building aseismic design, the stiffness and deformability properties of only structural components (frame elements, RC shear walls, etc.) are directly considered. However, this model formulation approach in many cases may be quite unrealistic, since stiffness contribution of nonstructural elements, like different types of infill walls, may be of great importance. In addition, for analysis of structural cumulative vulnerability, accumulated damage in nonstructural elements must be considered since its resulting losses may be very high.
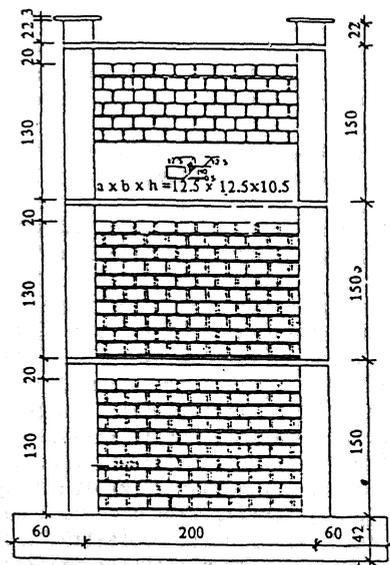
To investigate damage propagation in nonstructural infill components under excessive loads and its resulting effects to actual inelastic hysteretic response characteristics, five nonlinear tests of three-story frame models (Fig. 1) have been performed under simulated interactive effects of constant vertical and earthquake-like cyclic lateral loads. The first nonlinear comparative test is performed considering three-story frame model without infill components. Typical recorded force-deformation hysteretic relation from this test is shown in Fig. 2. The next four experimental tests are performed considering the same RC frame model, but with the included four different types of infill components as follows: (1) brick masonry infill, (2) syporex infill, (3) gypsum infill, and (4) eltozol infill, which are most frequently applied in recent practice. Qualitative differences in inelastic response properties of the tested models may be noticed from the recorded force-deformation hysteretic relations as can be seen from Figs. 2 and 3 for the case of the tested frame without and with brick masonry infill, respectively.

Based on obtained experimental results from the tested RC frame models without and with infill components, it is clear that the effect of nonstructural infill may be very significant to actual hysteretic response of the integral structure and has to be realistically considered in the formulated analytical model, as well as in the analysis of building vulnerability under earthquake ground motions. Considering available experimental evidence, appropriate analytical models for inelastic response simulation of both structural and nonstructural components are developed. Model input parameters and respective inter-story drifts con-

Figure 1. Tested RC frame model without and with four different infill types

Table 1. Nonlinear characteristics of five tested three-storey RC frame models without and with different infill

Three Storey RC Frame Without Infill	RC Frame Model Parameters – Test Data						Inter Story Drift		
	DC (cm)	FC (t)	DY (cm)	FY (t)	DU (cm)	FU (t)	ΔC (‰)	ΔY (‰)	ΔU (‰)
1 Comparative Model	0.070	1.40	0.43	4.20	1.73	4.85	0.2	2.9	11.5

Three Storey RC Frame With Infill	Infill Model Parameters – Test Data						Inter Story Drift		
	DY (cm)	FY (t)	DU (cm)	FU (t)	DL (cm)	K1 (t/cm)	ΔY (‰)	ΔU (‰)	ΔL (‰)
1 Brick Masonry	0.192	8.00	0.666	9.27	2.58	42.7	1.5	5.1	19.8
2 Syporex	0.106	3.50	0.341	4.13	2.08	34.7	0.8	2.6	16.0
3 Gypsum	0.130	6.97	0.47	8.28	1.75	58.7	1.1	3.6	13.5
4 Eltozol	0.500	1.80	1.83	2.33	5.00	3.7	3.9	14.1	38.5

trolling damage propagation for the tested three-story frame models without and with infill elements are presented in Table 1. Capability of the analytical models to simulate hysteretic response of frame components, as well as infill components, is separately
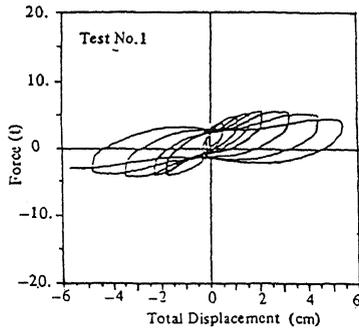
Figure 2. RC frame without infill - recorded hysteretic curve of storey-2

Figure 3. RC frame with brick masonry infill recorded hysteretic curve of storey-2

analyzed and confirmed through the plotted force-deformation relations based on performed nonlinear response analysis of the tested three-story frame model under real earthquake excitation. Finally, based on available experimental data, necessary damage criteria for different types of building components have been also determined in relation with the formulated element-based nonlinear analytical models.

2.2 Inelastic structural model and procedure for building vulnerability analysis

To achieve more realistic simulation of the inelastic structural response under earthquake excitation, the presently proposed new analytical model of the integral building is formulated considering inelastic behaviour properties of all constituent structural and nonstructural components. To reduce significantly the required computational time, the integral structure in the present case is represented by the shear-type model considering in the analysis the dominant lateral displacements at story levels as effective degrees of freedom. However, by incorporating the specific inelastic characteristics of all constituent structural and nonstructural components along with previously developed damage criteria, vulnerability analysis at the element level has been provided. Based on known element force and deformability capacity and available earthquake response statistics from the performed inelastic earthquake responses of the building under different earthquake ground motions and intensity levels *damage degrees* of structural and nonstructural components at story level have been determined and then directly used to develop corresponding *specific loss functions* of the integral building. Considering in the analysis representative sets of structural systems of buildings, the generated statistical set may be significantly improved and the resulting vulnerability predictive functions can be established to satisfy the required reliability level for seismic risk assessment.
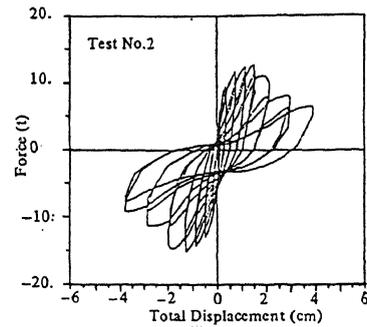
3 VULNERABILITY PREDICTION OF EXISTING BUILDINGS

In the course of the conducted recent investigations, several sets of different structural systems of existing nonearthquake and earthquake resistant buildings have been analyzed in all details using the presented methodology and procedure. The results of the studies performed for two representative types of non-earthquake resistant structural systems, i.e., nonmoment resisting reinforced concrete four-storey building and eight-storey reinforced concrete frame building with structural reinforced concrete walls in the staircase and elevator shaft are presented and discussed in this paper. Specific attention is given to the development of the vulnerability functions through detailed analysis and consideration of the load bearing and deformability capacity of structural and nonstructural elements; the obtained maximum relative deformation characteristics for the selected representative earthquake ground motions and their range of intensity; specific damage degrees in 5 basic categories related to the cost for repair and strengthening defined as specific loss for each building element, individual storey and integral building; presenting theoretical vulnerability functions as average specific loss of the entire building considering the effects of the selected set of the representative earthquake ground motions.

3.1 Computation of inelastic structural response

Inelastic structural response has been analyzed by implementation of the proposed shear-type dynamic models, formulated separately for the longitudinal and transversal directions of the buildings. Storey restoring force properties in the analysis have been represented separately for structural and nonstructural elements by respective hysteretic relations. The required input parameters have been determined based on detailed capacity analysis of the respective structural element and nonstructural components. To investigate the building inelastic dynamic behaviour under increasing earthquake intensities, peak ac-

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celerations of selected earthquake records have been varied starting from very low levels, i.e., PGA = 0.05 g, and increasing them in the subsequent analyses up to PGA = 0.40 g. Since the expected earthquake ground excitations were represented by the selected three acceleration time histories, (1) Ulcinj (Olimpic), Comp. N-S, Montenegro, Yugoslavia earthquake, April 15, 1979; 2) Bar (Assembly of the Community),-Comp. E-W, the same Montenegro earthquake; and 3) El Centro, Comp. N-S, Imperial Valley earthquake, May 18, 1940), and because their intensity levels were varied, the studies of each separate building resulted in the completion of a large number of nonlinear building response analyses. Naturally, significant dispersion of the computed earthquake demand parameters ISD (inter-story drift) have been obtained for the considered equal PGA's of different input earthquake motions, expressing basically the effect of their dominant frequency content variation. However, to simplify significantly structural vulnerability evaluation, it was considered reasonable to assume PGA as convenient earthquake intensity parameter, since the effects of frequency content variation have been somehow included through the selected representative set of three earthquake records.

3.2 Vulnerability functions of structural and nonstructural components

Using the estimated load bearing and deformability capacity of each storey elements as well as the obtained maximum response inter-story drift (ISD), considered as basic informations to relate progressive structural damage, or more specifically to evaluate damage propagation in the structural (SE) and nonstructural (NE) constituent elements of the integral building under earthquake ground motions. Consequently, for derivation of the relations between earthquake ground motion and structural response, the following assumptions were initially made: (1) since earthquake effect can be expected mainly in the longitudinal or transversal direction, building vul-

nerability is separately analyzed in both principal directions; (2) the earthquake response parameters computed for all considered earthquake records and different PGA levels are the basic earthquake response statistical data; (3) damage propagation in the structural components and nonstructural elements are primarily controlled by maximum response interstory drift (ISD); and (4) relations between earthquake motion and structural response have been separately derived for each story of the building. Following the above assumptions, the relations ISD-PGA have been established for each building storey and for both principal directions based on available statistical data from previously computed nonlinear structural responses.

The relationships between maximum inter-story drift and PGA's for the first storey of the two representative types of buildings are comparatively presented in Figures 4 and 5. It is quite evident that building no. 2 with reinforced concrete elements possesses damage controlled capability (Figure 5) which is not the case with building no. 1 (Figure 4) even for the lowest earthquake intensity.

Based on the analyses performed on the specific loss for the structural and nonstructural elements and the entire building for each of the considered earthquake ground motions (as presented in Figures 6 and 7 for building no. 2), average analytical vulnerability functions have been obtained and presented in Figure 8 for building no. 1 (nonearthquake resistant RC frame) and Figure 9 for building no. 2 (nonearthquake resistant RC frame with structural walls), as an average of the selected three representative earthquake ground motions.

Considering average specific loss as percentage of the total building cost per unit area, vulnerability functions of buildings no. 1 and no. 2 (Figures 8 and 9) are clearly representing damage capability control for different excitation level. For example, building no. 1 shows extremely high vulnerability, compared with building no. 2 which possesses damage controlled capability to PGA of about 30% g of the structural elements (specific loss 25%), but economically not
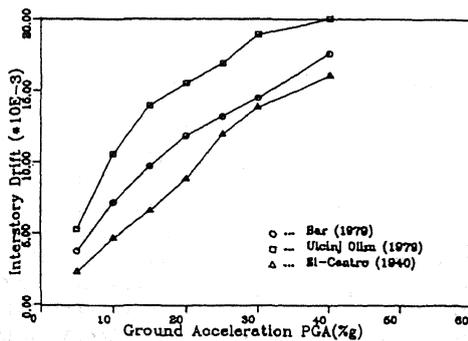
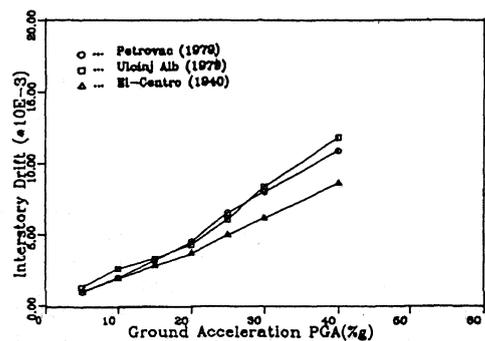Figure 4. Interstorey drift relations for the first storey of building type no. 1

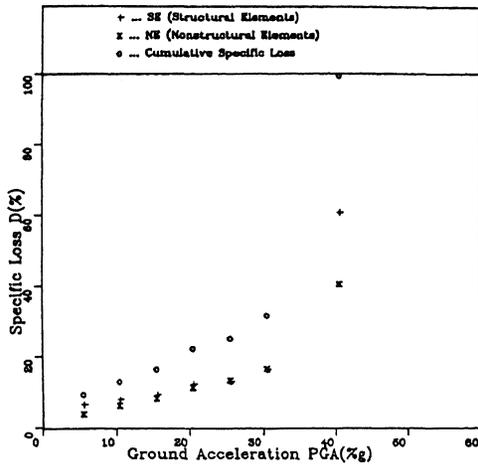Figure 5. Interstorey drift relations for the first storey of building type no. 2

Figure 6. Specific loss relations of building no. 2 for increasing intensity levels of selected earthquake type 1.
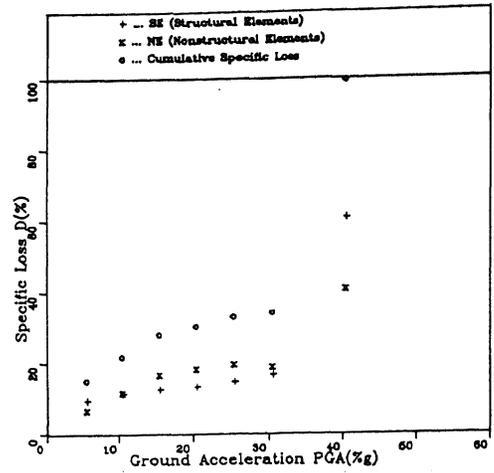

Figure 7. Specific loss relations of building no. 2 for increasing intensity levels of selected earthquake type 2
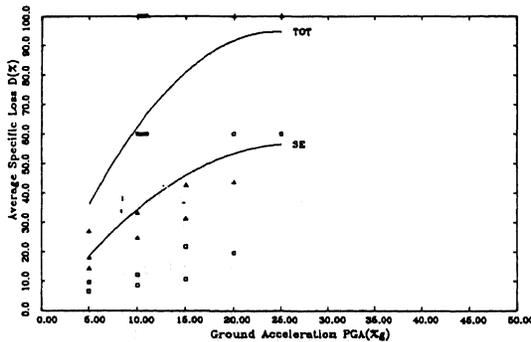

Figure 8. Average analytical vulnerability functions of building type no. 1 for selected three earthquake ground motions (nonearthquake resistant RC frame)
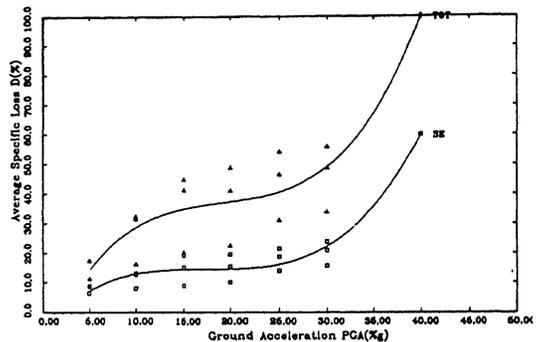

Figure 9. Average analytical vulnerability functions of building type no. 2 (nonearthquake resistant RC frame with structural walls) for selected three earthquake ground motions.

justifiable total loss of 40% which is dominantly due to nonstructural damage.

4 CONCLUSIONS

Considering that the existing stock of residential and commercial buildings, schools and hospitals, and other public facilities, is dominated by presence of highly vulnerable brittle reinforced concrete and masonry buildings as well as insufficient and nonuniform presentation of the effects of the past earthquakes for development of empirical vulnerability functions, the future efforts should be concentrated on the development of the experimentally verified theoretical vulnerability functions in order to assume reliable basis for planning of seismic risk mitigation. The presented attempt for development of theoretical vulnerability

functions could be implemented for prevailing categories considering specific construction technologies and quality of construction in earthquake prone countries and regions.

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