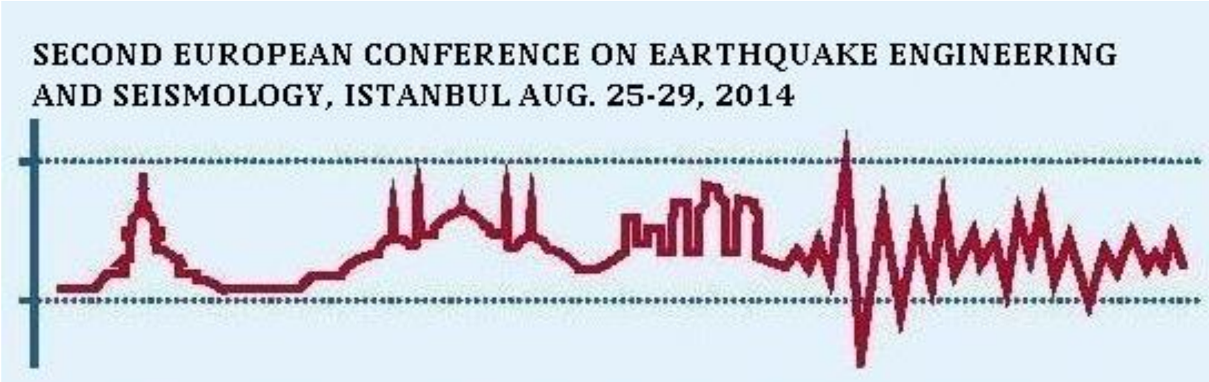

USE OF NON-LINEAR DYNAMIC ANALYSIS IN THE ASSESSMENT OF SEISMIC VULNERABILITY OF BUILDINGS

Luis YAMIN[1], Alvaro HURTADO[2], Raul RINCON[3], Alex H. BARBAT[4] and Juan REYES[5]

ABSTRACT

The seismic vulnerability functions are a useful tool to evaluate the response of typical structural systems in terms of structural damage or economic losses given a seismic intensity measure. They are used as part of risk assessment models together to the hazard representation and exposed assets databases, to obtain representative physical or economic loss figures of entire countries, cities, regions or any other portfolio of infrastructure components. This paper explores the possibility of using non-linear dynamic analysis to estimate the seismic vulnerability functions of representative building classes. For the purposes of the analysis, two different archetype reinforced concrete moment resisting frames (MRFs) are designed following conventional seismic specifications. For each one of the archetype buildings, non-linear dynamic analyses are conducted to estimate representative engineers demand parameters (EDP). Estimated damage functions are then assigned to the main structural components, particularly beams and columns. In this approach, the plastic rotation is selected as the main EDP for the evaluation of damage at individual elements. Finally, the vulnerability functions for the archetype buildings are presented in terms of mean damage ratio at different spectral acceleration levels. Comparison with equivalent seismic vulnerability functions proposed in selected references is presented in order to validate the methodology. Conclusions and recommendations for further development and applications are included.

Keywords: Seismic vulnerability functions, damage functions, economic losses, archetype buildings.

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INTRODUCTION

Estimating probable damages and losses due to earthquakes in urban areas, has created powerful incentives for countries to develop integrated disaster risk management programs including mitigation programs for vulnerability reduction, planning options and tools, financial retention and transfer strategies, emergency response plans, cost-benefit analysis for retrofitting programs and others risk measures.

The seismic vulnerability functions have been a useful tool to evaluate the response of typical structural systems in terms of percentage of structural damage or economic losses given a seismic intensity measure. They have been used as part of risk assessment models together to the hazard representation and exposed assets databases to obtain representative physical or economic loss figures of entire countries, cities, regions or any other portfolio of infrastructure components. Specific practical examples of probabilistic risk models include those from insurance companies, which have developed proprietary specialized software to estimate financial risk using figures such as the pure premium, average annual loss or maximum probable losses. Some of these models require the simplified representation of the vulnerability of typical building classes or representative infrastructure components. Another example is the global risk assessment made in the framework of the UNISDR's Global Assessment Report on Disaster Risk Reduction, UNISDR GAR13 (2013), and Yamin et al. (2014-2) which uses a set of vulnerability curves suitable for a probabilistic global risk assessment. These functions establish the relation between the intensity of the hazard event and the mean damage ratio, MDR, of the particular component which it represents.

This paper intends to evaluate the possible use of nonlinear dynamic analysis to estimate the vulnerability functions of typical buildings. The methodology is partially based on references (Porter K and Kiremidjian A, 2001; Yamin et al., 2012). For the purposes of the analysis, two different archetype building models are designed. They represent reinforced concrete moment resisting frames (MRFs) having a 5-stotry height and two different design levels: high and low seismic dissipation capacity. Then, the fundamentals of performance based engineering (PBE), as described in the ATC (1996) and NEHRP (2003) are used to study the structural behavior beyond the yield point (elastic limit) and up to the collapse of the building. The archetype buildings are designed according to standard seismic specifications keeping strictly control of all the design parameters. Once the building is completely designed and characterized, a full nonlinear dynamic analysis is performed in order to adequately characterize the seismic response of the building. Seismic response is studied through the definition of selected engineering demand parameters. Damage functions are then used to estimate the mean damage ratio at each intensity level.

For the present analysis, only the seismic input variability is considered. All other variables including geometrical configuration, material properties, structural member capacities, loads, and other required parameters are considered as deterministic.

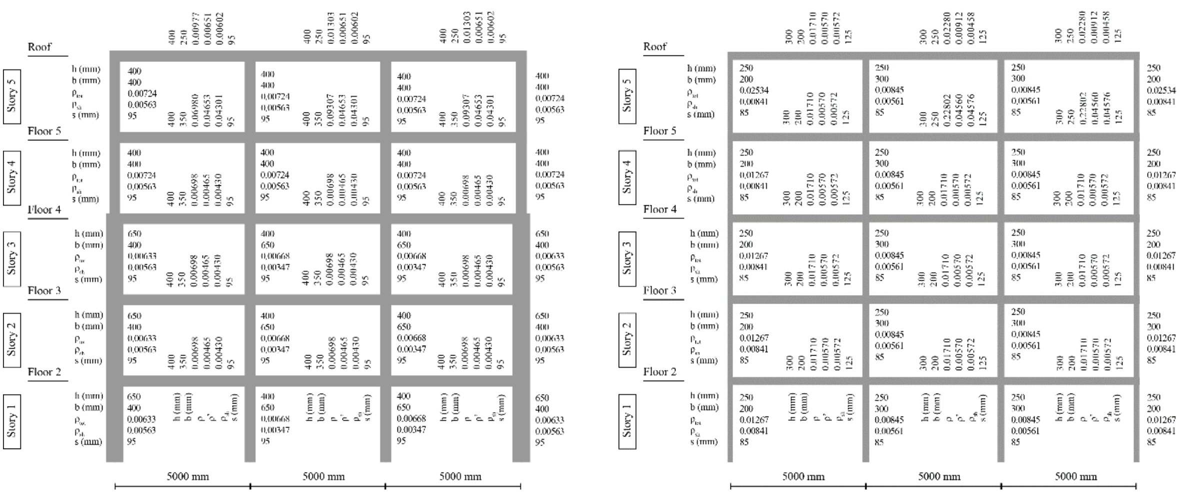
METHODOLOGICAL APPROACH

Analytical procedure

The assessment of the seismic vulnerability of representative buildings can be studied through detailed nonlinear dynamic analysis of representative archetype buildings. Non-linear dynamic analysis requires the definition of a complete integrated 3D analytical model of the building construction, including the definition of potential plastic hinges at critical elements. Widely used commercial computer program already include those analytical features (Perform 3D, SAP2000, OpenSees). For the analysis, specific site earthquake signals are defined in order to consider possible variations in the intensity and frequency contents of the earthquake input. Methodologies for selecting the best possible signal are already proposed in the literature (Reyes J and Chopra A, 2011; Reyes J, 2009). Representative engineering demand parameters (EDP) are obtained for increasing seismic intensities. EDP usually includes maximum values of inter-story drift, floor accelerations, inelastic rotation and shear demands at critical elements (Haselton C, 2006). Using these demand parameters, the estimation of local and global damage in the building can be addressed. For the present analysis, only direct structural damage is considered for the main structural elements of the building. Damage is expressed by damage functions of each particular sub-component of the building. Results are expressed in terms of vulnerability functions, relating the mean or expected damage ratio of the building and any selected seismic intensity parameter, the spectral acceleration in the present case.

Archetype building models for analysis

In order to completely characterize an archetype building model, it is necessary to specify a great number of parameters (Yamin et al., 2014-1). Those include design parameters used to define the archetype model such as geometry, cross section dimensions of main structural elements, particular modeling considerations (rigid diaphragm, fixed restraints at column bases, rigid zones at nodes, etc.), dead and live loads, seismic design level, reinforcement details and others.



(a) (b)

Figure 1. Geometric and steel detailing characterization of archetype building models, (a) Model No. 1 designed for special seismic considerations, (b) Model No. 2 designed for no seismic considerations

Figure 1 represents some of the main parameters required for such characterization for representative 2D frames selected from the complete 3D archetype model. In order to maintain consistency with real engineering practice, the final design configuration and the steel detailing of all building models were validated by a practitioner engineer (Forero J, 2013).Two different design levels are considered: one designed for full seismic design consideration in a high seismic hazard zone (Aa=0.25g) and the other designed for minimum design gravity load consideration and no special seismic requirements.

Seismic records for analysis

A total of 18 seismic records have been selected for the nonlinear dynamic analysis. Records were selected using the PEER-NGA Strong Motion Database. The criteria for the selection was the following:

- Magnitude, Mw > 6.5.
- Effective peak acceleration > 0.2g and effective peak velocity >15 cm/seg.
- Maximum six different records from the same earthquake, selecting those of greater PGV (Peak Ground Velocity).
- Maximum representative frequency < 0.25 Hz to guarantee the participation of low frequencies.
- Events from normal, inverse or strike slip faults.
- Only free field records.

Figure 2 illustrates the acceleration elastic response spectrum for 5% damping of the selected records. The mean spectral values are indicated as well as the + and – standard deviation curve.

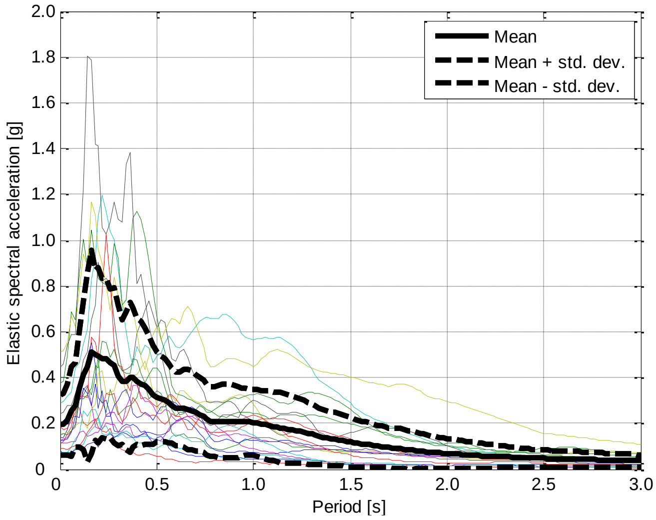
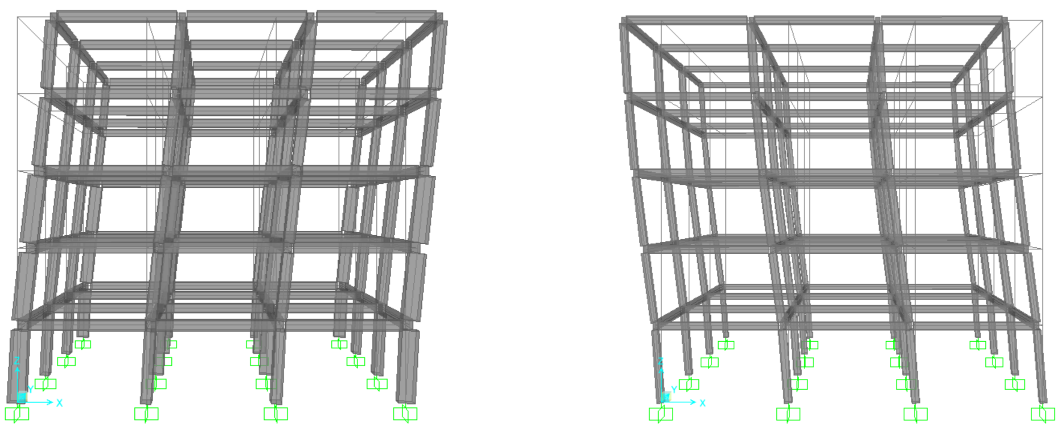


Figure 2. Elastic acceleration response spectrum for 5% damping of the selected records

Non-linear dynamic analysis of archetype buildings

For each one of the archetype building models, nonlinear dynamic analyses following the requirements of ASCE (2007) are conducted to estimate EDPs such as base shear demands, maximum inter-story drifts, floor accelerations, plastic hinge rotations and internal forces in critical elements.

Nonlinear analyses are performed for the general 3D model of the building. However, in order to clearly identify the seismic response, only one principal direction of analysis is considered. Reinforcement slip is not considered in the building models. Only primary structural elements are considered in the analysis. No shear deformations and capacity of beam-column joints is considered. Rigid diaphragms are considered in all cases. Dead loads are applied previously to the calculation of the dynamic response. Plastic behavior is considered through plastic hinge elements located at the column and beam ends. Moment capacities are calculated for each hinge considering the non-linear behavior for steel and concrete components of each cross section. Steel is modeled using bi-linear model, while confined concrete is modeled using reference (Mander et al., 1988). Plastic rotation capacities are calculated using Tables 6.7 and 6.8 from reference ASCE (2007). Although no shear hinges are considered in the model, verification of non-shear failure are performed for critical elements in all analysis. All analyses are performed using the computer program PERFORM 3D V5.0 completed with some verifications using computer program SAP2000 V15.1.1. Figure 3 illustrates the 3D model and the first fundamental vibration mode in the direction of analysis.



(a) (b)

Figure 3. 3-D models for analysis and fundamental vibration modes (a) Model No. 1 and (b) Model No. 2

Results

Figure 4 illustrates the fundamental mode pushover curves for each one of the archetype buildings studied. In each case, different reference points are illustrated along each one of the pushover curves: the first steel yield point in the model, the probable collapse point (defined as the one where horizontal deformation increases considerable) and the first appearance of non-linear performance points (IO=Immediate Occupancy; LS=Life Safety; CP=Collapse Prevention) (ASCE, 2007).

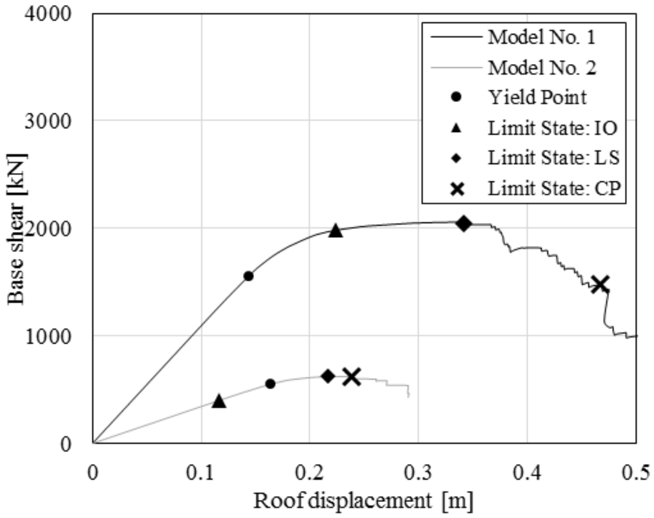


Figure 4. Summary of pushover analysis and non-linear performance points

Figure 5 shows equivalent results in the standard incremental dynamic analysis (IDA) format which allows the determination of the collapse point for each earthquake record in each archetype model. Collapse points are selected as the point in the curve where horizontal deformation increases considerable (Haselton C, 2006).

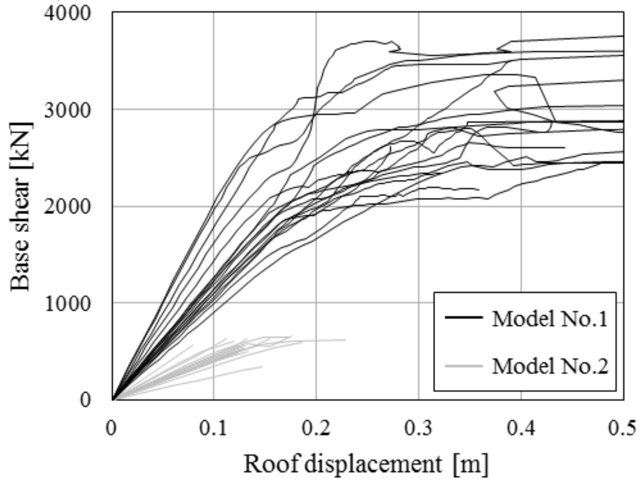


Figure 5. Incremental dynamic analysis (IDA) curves for Models No. 1 and No. 2

Figure 6 summarizes the results for the EDP corresponding to plastic beam and column rotations. These are the main parameters used for the estimation of structural damage for each one of the buildings in the present approach.

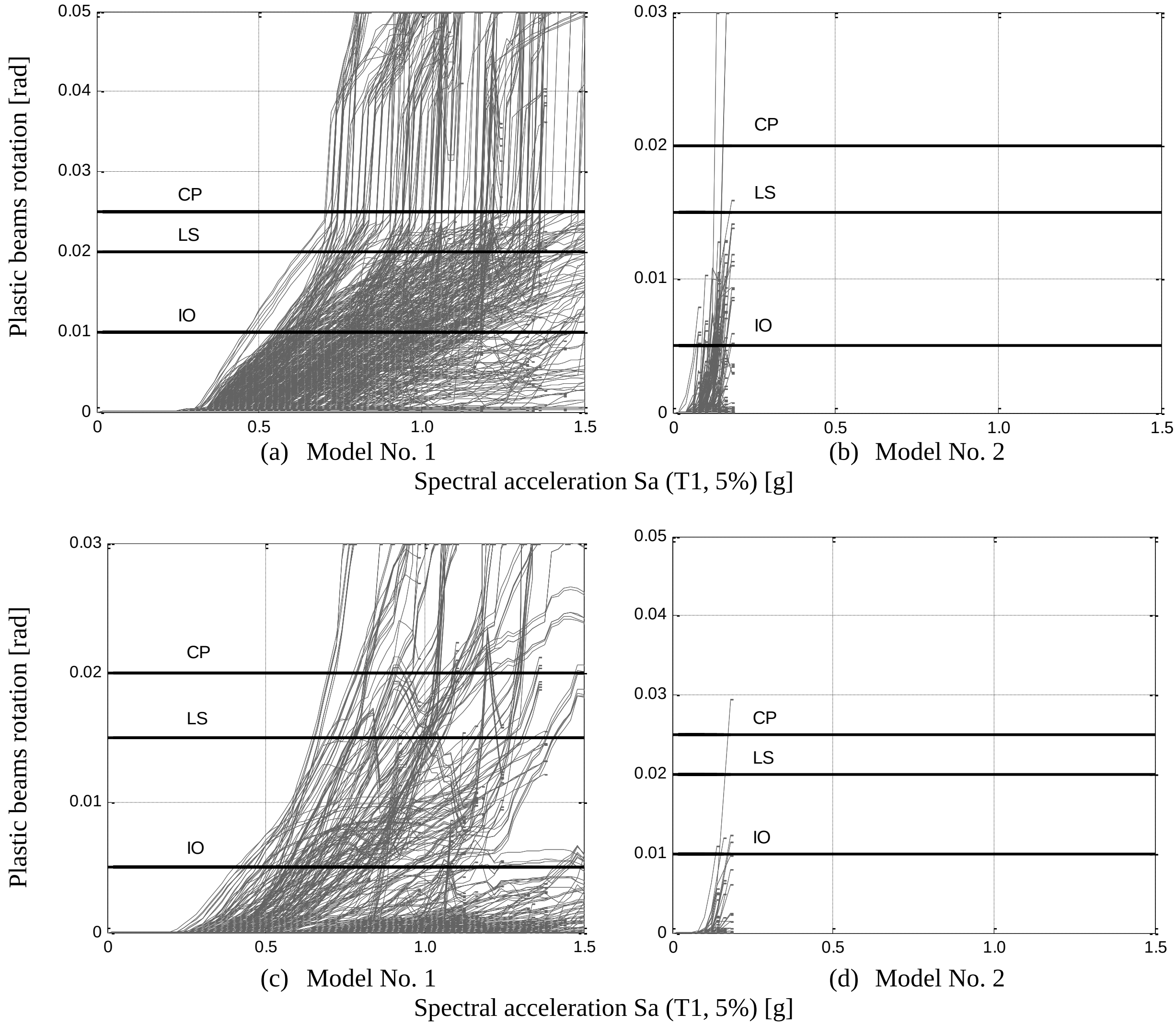


Figure 6. Plastic beam rotations for models (a) No.1, (b) No. 2 and plastic column rotations for models (c) No.1 and (d) No. 2

Damage functions for main structural elements

In order to establish a relation between the previous demand parameters and the estimated damage, damage functions are proposed for each representative structural element subjected to suffer damage under seismic loads (Yamin et al., 2012). The damage functions are defined as step functions with four (4) levels of damage: non-damage, slight damage, severe damage, complete damage. A representative damage factor is assigned to each damage level, based on expert judgment and reported case studies of buildings subjected to repair and retrofit. A validation with practitioner architects was also made in order to insure reasonable final figures (Escovar, 2013). The limits for each damage level are defined based on performance values given in ASCE (2007) for the corresponding building class.

Figure 7 shows illustrative damage functions for main structural elements in the studied archetype buildings.

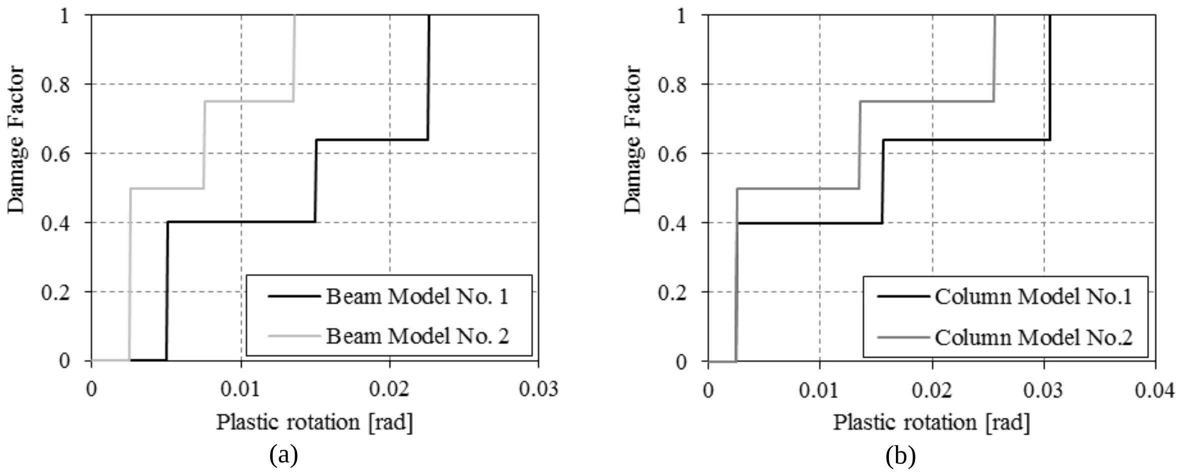


Figure 7. Representative damage functions for main structural elements a) Beams and b) Columns

Vulnerability functions

Using the engineering demand parameters obtained from the nonlinear dynamic analysis and the previously presented damage functions, vulnerability functions for the entire building can be estimated integrating the individual damage factors for all structural elements at selected seismic intensity levels. The results of such analysis for the two archetype buildings are shown in Figure 8 and 9. Each mean damage ratio function is accompanied by the corresponding variance at each seismic intensity level. The corresponding vulnerability function for a 5 story moment resisting frame estimated using the parameters proposed by FEMA (2011) following the methodology proposed by Yamin et al.(2014-2) are also included in each figure for comparison purposes.

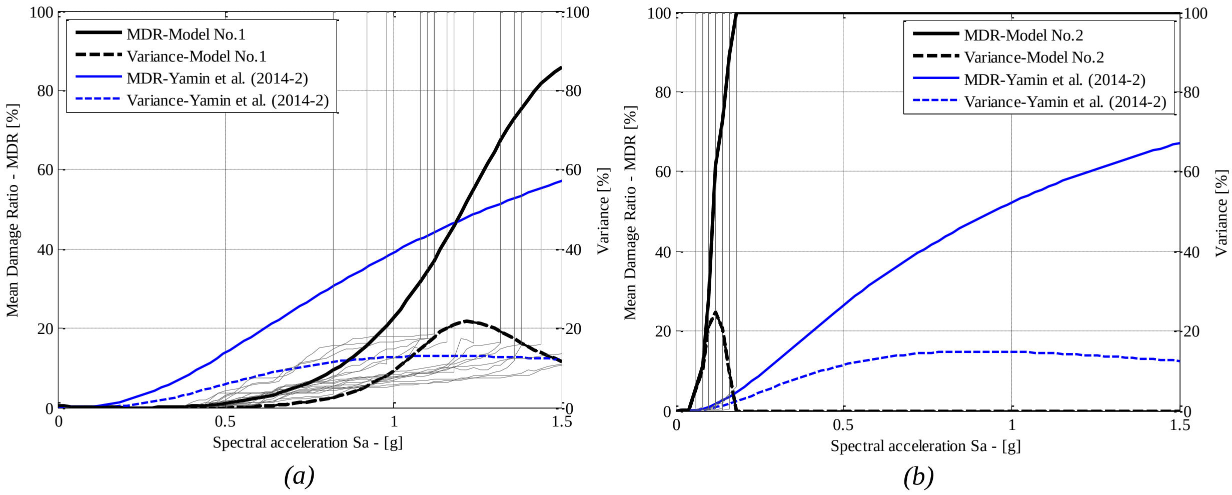


Figure 8. Vulnerability functions for the two archetype models, (a) Model No. 1 and (b) No. 2.

CONCLUSIONS

The possibility of using non- linear dynamic analysis of representative buildings to evaluate the seismic vulnerability functions is demonstrated using two different archetype reinforced concrete moment resisting frames (MRFs) models. For each one of the models, dynamic nonlinear analyses are conducted to estimate representative engineers demand parameters (EDP). Estimated damage functions are then assigned to the main structural components, particularly beams and columns. In this approach, the plastic rotation is selected as the main EDP for the estimation of damage at individual elements. Finally, the vulnerability functions for the archetype buildings are presented in terms of mean damage ratio for different spectral acceleration.

The methodological approach requires further refinement in the following aspects:

- Include different building configurations.
- Consider both structural and non-structural components damage.
- Refine the estimation of the damage factor and the integration of results.
- Extensively compare the obtained results with other similar published results.
- Analyze the sensibility to structural variables such as design code level, type of confinement for RC elements, type and ductility of joints for steel structures, the structural participation of masonry in the building behavior and other related variables.
- Estimate uncertainties associated with the geometrical configuration, material properties, loads and epistemic uncertainties as well.

As a general conclusion, the use of non-linear dynamic analysis in the assessment of seismic vulnerability of representative buildings is a promising methodological approach despite the very high analytical and computer effort involved.

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