SEISMIC PERFORMANCE OF MASONRY BUILDINGS SUBJECTED TO SYNTHETIC GROUND MOTIONS

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ABSTRACT:

This study mainly focuses on the response statistics of unreinforced masonry (URM) structures subjected to synthetic ground motions from a major earthquake. URM structures are idealized as equivalent single-degree-of-freedom (ESDOF) systems, and the global structural parameters are determined based on the inherent characteristics of this specific construction type. The nonlinear dynamic analyses are carried out by using the simulated ground motion dataset developed for the 12 November 1999 Düzce earthquake and scenario events in the region. The earthquake stations which are generated to investigate the effects of the fault rupture location, soil types and distances to the fault rupture location are randomly selected with respect to the peak ground acceleration (PGA) obtained from the scenario earthquake with a magnitude of 7.1 for soft soil. The seismic responses obtained from the analyses are compared with predefined limit states, and the sensitivity of different seismological and structural parameters on the seismic performance of URM structures is assessed. The whole range of seismic response is monitored by considering three limit states, or in other words, four damage states from no damage to collapse. The reliability of the response statistics is verified by discriminant analysis. The results reveal that synthetic ground motion records are suitable for parametric analyses of seismic response of structural systems since they can cover all the required range of values for the seismological parameters and they can be simulated for a specific region with unique characteristics. The results also reveal the structural parameters that are more pronounced for brittle and rigid masonry structures when they are subjected to simulated ground motion records.

KEYWORDS: Equivalent SDOF Model, Simulated Ground Motion, Unreinforced Masonry, Nonlinear Dynamic Analysis, Limit State, Discriminant Analysis.

1. INTRODUCTION

Unreinforced masonry (URM) is one of the oldest known construction types where structures are constructed with the combination of mortar and masonry units, commonly termed as clay brick, concrete block, irregular stone, and adobe. Owing to their lower tensile strength capacity from the combination of mortar and masonry units, URM structures represent brittle behavior under earthquake excitation. In addition to this, their load-bearing masonry walls contribute to the structural system by carrying vertical and horizontal loads. They have high inertial responses to the earthquake action due to their large masses. They are dominantly constructed up to two stories in rural areas of Turkey. Furthermore, the design recommendations for URM structures and their quality control are not properly implemented in Turkey so that they are called as non-engineering structures, which mostly conceive severe damage or collapse after even a moderate seismic action.

In this study, the seismic performance of URM structures are investigated by using simplified structural modeling and dynamic analysis through simulated ground motions. Structural analyses are carried out with simulated ground motion datasets obtained from the simulated records of the 12 November 1999 Düzce earthquake as well as scenario events in Düzce and the simplified Equivalent Single Degree of Freedom (ESDOF) models of the URM structures. The simulations of the 1999 Düzce earthquake include scenario earthquakes with different magnitudes, source-to-site distances and site conditions. Accordingly, the damage state (DS) of a structural model due to a given seismic excitation is determined via comparing displacements obtained from the dynamic analyses with its predefined limit states. Considering these performance levels of URM structural models, the influences of different seismological and structural parameters are investigated with probabilistic approaches and a statistical tool.

2. SEISMIC ANALYSIS OF URM STRUCTURES

The increasing complexity of structures both in elevation and plan, in addition to the diversity of architectural styles require complex analytical models with structure-specific members and many structural parameters to be defined. As a result, structural analysis takes more time and computational effort and also requires well expertise in terms of the structural system. This issue becomes even more critical in the case of multiple structural simulations in order to assess seismic vulnerability of these complex structural systems. Hence, the researchers in the field generally employ simplified approaches to eradicate this problem. One of the most common approaches is to obtain a simple structural system from the capacity curve of a complex structure with pushover analysis. The simple structural model is called as an ESDOF model. The main target of an ESDOF model derived from the multi degree of freedom (MDOF) model is to simplify structural complexity in a reliable manner, to obtain the structural analysis results more easily and to interpret the effect of different parameters on the structural response. This process is carried out to obtain the capacity curve with pushover analysis for MDOF model; thus, it enables to generate the capacity spectrum of the ESDOF model.

The material model of ESDOF system is the modified Ibarra-Medina-Krawinkler (MIMK) deterioration model with peak oriented hysteresis response, which simulates all types of degradation of the structure or the component under the cyclic loading shown as Figure 1 in the form of a cyclic moment versus chord rotation relationship. The cyclic moment versus chord rotation relationship is used by converting it into a cyclic force-displacement relationship of the ESDOF model. There are three cyclic deterioration modes in the MIMK deterioration model with peak oriented hysteretic response; basic strength deterioration, post–capping strength deterioration and unloading stiffness deterioration, respectively.

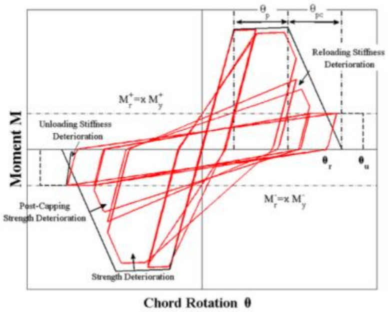

Figure 1. The MIMK deterioration model with peak oriented hysteretic response, Lignos and Krawinkler (2012)

Representing all seismic intensity levels using recorded ground motions of regional seismic character is not possible given the inherent sparse nature of moderate to large earthquakes. For these purposes, this study is conducted by using simulated earthquake dataset, which was developed by Karimzadeh et al. (2017) using ground motion modeling of the 12 November 1999 Düzce Earthquake. For the simulation of the ground motion records, the stochastic finite-fault method, based on dynamic frequency approach, was utilized (Motazedian and Atkinson, 2005). Stochastic finite fault method can be utilized for real and scenario events at dummy stations, where there are no real records with the simulation parameters. It must be noted that the simulation parameters are first validated at real station locations by comparing against real records. Then, they are used to simulate acceleration records at dummy stations. In the stochastic finite fault method, smaller sub-faults are initially defined on the original rectangular fault plane with discretization. Thus, each sub-fault can be associated with a stochastic point source and the motions of each sub-fault are accumulated to model the acceleration time histories of the 1999 Düzce earthquake at the selected dummy and real stations. In this study, the recording stations, which are used to investigate the effects of source, soil types at the stations and source-to-site distance are randomly selected from simulated records of the 1999 Duzce earthquake. This earthquake is characterized by a right lateral strike-slip fault rupture with a moment magnitude (M_w) of 7.1, and it caused thousands of fatalities and injuries as well as extensive damage to structures (Sucuoğlu, 2002).

Scenario events of magnitudes M_w= 5.0, 5.5, 6.0, 6.5, 7.0, 7.1 were simulated in Karimzadeh (2016) for two site conditions, which are classified as the soft and hard soil type. Out of 280 dummy stations, 20 of them are selected in this study as represented in Figure 2. Therefore, 240 distinctive time-history earthquake records are obtained to carry out nonlinear dynamic analysis of the ESDOF models.

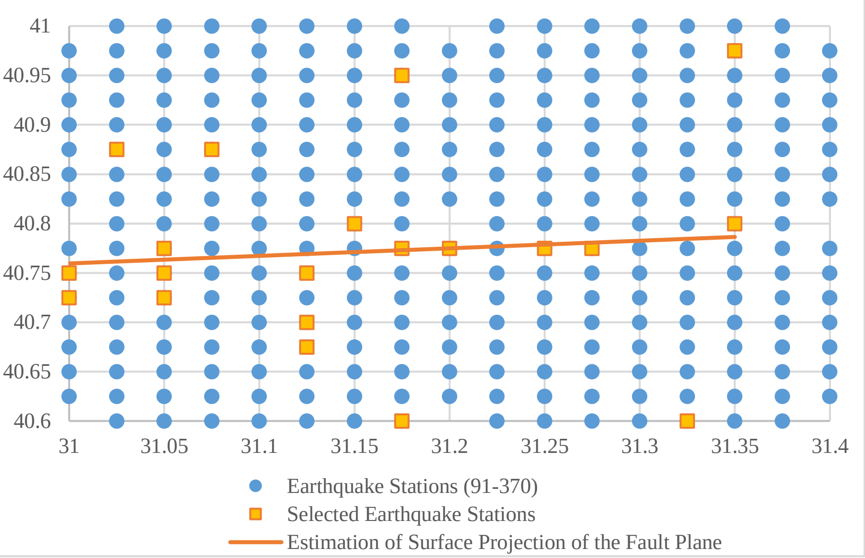

Figure 2. The 280 dummy earthquake stations defined in Karimzadeh (2016) in the smaller box within the Duzce region

PGA is employed as the major parameter to select the earthquake dummy stations and the corresponding stations since it is dominantly effective in representing the seismic response of URM structures. Therefore, selection of the earthquake dummy stations is carried out by using the PGA values between 0.1g and 1.0g taken from the M_w=7.1 scenario for the soft soil condition. The same stations are used for the entire magnitude range of interest. The PGA values are equally divided to ten intervals to have a minimum of random two PGA values at each interval. The purpose is to cover all the range of seismic response from the elastic behavior to collapse for the ESDOF models considered.

Even though ground motions result from complex phenomenon beneath the ground during earthquakes, the differences of PGA values among the earthquake stations for the same moment magnitude are usually due to two fundamental independent variables, namely the site condition and distance of the earthquake stations to the fault. The site classes are defined as a function of the top 30-meter average S wave velocity Vs30 while the distance metric used in this study is Joyner-Boore distance (R_{JB}), which is defined as the shortest horizontal distance to the surface projection of the rupture area. Generally, R_{JB} is a better metric to represent the effect of fault rupture particularly for large earthquakes.

The URM structures are modeled with the OpenSees software command rules for the node, element, constraint, material property, and element section. The ESDOF models are defined by the model basic command. Each node of the model is described and assigned to construct a nodal object. The element of the model is constituted among the 1st and 2nd nodes. The single-point homogeneous boundary constraint is assigned to the 1st node as fully fixed support. The hysteretic response is considered with MIMK deterioration model with the peak-oriented to demonstrate the force-displacement relationship of the model under the lateral loads. The section of the object is identified as the uniaxial section that enables to represent a single section force-deformation response quantity. The rotational hinge also captures the nonlinear behavior of the element; therefore, it is used to represent a bilinear hysteretic response based on the MIMK deterioration model. In addition to these, total weight of URM buildings are estimated by considering their preselected vibrational values and the plan geometry of URM buildings is also presented with the values of top view in Table 1.

Table 1. *The weight of the structure with respect to the fundamental period*

Period (second)	Number of stories	Width (meter)	Length (meter)	Unit weight (kN/m^2)	Total weight (kN)
0.05	1	10	10	15	150
0.1	2	10	10	15	300
0.2	3	10	10	15	450
0.3	4	10	10	15	600
0.4	5	10	10	15	750

The prominent structural parameters, namely fundamental period, strength ratio, ductility ratio, post-yielding ratio, post-capping ratio, residual strength and hysteresis model degradation parameter are investigated to elaborate their effects on URM structures in terms of seismic vulnerability. In order to conduct a parametric study, the considered parameters are varied in discrete values within a range of minimum and maximum limits, which are determined by the local characteristics of masonry structures.

As shown in Table 2, discrete values are assigned to 7 different structural parameters related to the considered hysteresis model. Among these, period, strength ratio and ductility ratio have 5 different values whereas the remaining parameters have 3 different values, each containing a central (average) value and deviations from this central value for both favorable and unfavorable conditions. If all different combinations of structural simulations are considered, it makes up to 10,125 cases. In terms of seismological parameters, magnitude (M_w) is considered with 6 discrete values (5.0, 5.5, 6.0, 6.5, 7.0, 7.1), R_{JB} distance has 5 different intervals (0-5 km, 5-10 km, 10-15 km, 15-20 km, 20-25 km) and finally there are two different soil conditions (hard, soft) as obtained from the simulated ground motion database. When 20 different earthquake stations are selected for the synthetic records with 6 different magnitudes and 2 different soil conditions, the total number of records used in the dynamic analyses is 240. Hence when structural simulations are subjected to this selected set of records, the total responses of analyses are counted as 2,430,000. This is also equal to the number of response data in terms of damage state (DS), which is considered to evaluate the results of the parametric study.

Table 2. *Assigned values of structural parameters for URM buildings*

Vibrational Properties	**Very rigid**	**Rigid**	**Average**	**Flexible**	**Very flexible**
Period (T)	0.05	0.1	0.2	0.3	0.4
Seismic Performance	**Very poor**	**Poor**	**Moderate**	**High**	**Very High**
Strength Ratio (η)	0.1	0.3	0.5	0.7	0.9
Ductility Ratio (μ)	2.0	2.5	3.0	3.5	4.0
Post-yield ratio (α_s)		0	0.05	0.1	

Post-capping ratio (α_r)		-0.4	-0.3	-0.2	
Residual strength ratio(λ)		0	0.2	0.4	
Model degradation parameter (γ)		200	400	800	

As mentioned previously, approximately 2.5 million dynamic analyses are carried out in this study in order to investigate the influence of seismological and structural parameters on the seismic performance of URM structures. This is a huge number of analyses and can only be realized in the case of SDOF analysis demanding little computational effort, where a single analysis takes a few seconds. All of the analyses have been carried out with the OpenSees software. The Newmark integration method has been used to obtain the numerical results of SDOF analyses. The following sections are devoted to the presentation of the seismic analyses results and their statistical evaluation.

3. ASSESSMENT OF PERFORMANCE FOR URM STRUCTURES

This part focuses on the sensitivity analysis regarding the effect of different seismological and structural parameters on the seismic performance of URM structures. Structural modeling and idealization of URM structures were discussed and the modeling parameters were determined in the previous part. In this part, results of the dynamic analyses are evaluated using a parametric approach and the significance of each parameter is assessed in a detailed manner. In this study, the limit states (LS) are defined in terms of the yielding displacement (u_y), capping displacement (u_c), residual displacement (u_r) and ultimate displacement (u_u) for each structural simulation. These limit states are indeed the bounds of the damage states (DS), which are employed to determine the performance levels of URM models. These damage states are used to assess the influence of different seismological and structural parameters on the seismic performance of URM models.

Limit states are predefined specific performance thresholds, which are expressed in terms of a local or a global structural parameter such as capacity, stress, displacement, strain, rotation, etc. They have been commonly used within the last decades in performance-based design and analysis methodologies, seismic risk assessment studies, earthquake damage and loss estimation approaches. Exceedance of LS leads to the conditional performance of that specific structure, called as a damage or performance state. The concept of LS is employed to define DS due to the exceedance or non-exceedance criteria, meaning that LS-1 is a threshold between DS-1 and DS-2, LS-2 between DS-2 and DS-3 and LS-3 between DS-3 and DS-4. Table 3 shows the relationship between LS and DS for a generic case. Hence if there are three LS defined, this means there should be four damage states ranging from the elastic behavior to collapse.

Table 3. *General Definitions of Limit and Damage States*

LS	**Definition of Limit State**	**DS**	**Definition of Damage State**
LS-1	Immediate Occupancy	**DS-1**<LS-1	Very limited structural damage
LS-2	Damage Control	LS-1<**DS-2**<LS-2	Moderate damage-repairable
LS-3	Life Safety	LS-2<**DS-3**<LS-3	Significant damage – non repairable
LS-4	Collapse Prevention	LS-3<**DS-4**	Severe damage / partial collapse

Sensitivity analysis is essential to investigate the influence of the seismological and the structural parameters on DS. In this study, sensitivity analyses are conducted by considering all of the possible discrete values of a selected structural parameter while keeping the other parameters constant at their central (average) values. The mean values of DS (i.e. DSM) are obtained by taking the mean of all DS values obtained from dynamic analyses for that specific combination of parameters. In order to quantify the mean value, weighting factors are provided for DS-1, DS-2, DS-3, DS-4 as 1.0, 2.0, 3.0 and 4.0, respectively.

The results obtained from nonlinear dynamic analyses for the most favorable, average and unfavorable performance values of URM buildings for hard and soft soil conditions are examined to reveal the influence of moment magnitude and R_{JB} distance interval on DS. According to the results of sensitivity analyses for seismological parameters, it can be stated that

- Damage level of the structures generally increases with larger magnitude values as expected.
- If R_{JB} distance increases, the effect of the ground excitation becomes smaller causing a decrease in the damage levels. The site conditions are generally effective on damage levels with magnitude values M_w>6.0 within the distance interval (0-5) km. In general, shifting from soft to hard soil conditions decreases the damage level of the structures for the same magnitude and R_{JB} distance interval.
- DS is prone to decrease from the lowest performance level to the highest performance level of the structural parameters, respectively.
- DS are unexpectedly higher in some farther R_{JB} distance intervals than the closer ones. Sucuoglu (2002) stated that larger ground motion amplitudes can be obtained at farther earthquake stations in the case of Düzce earthquake. This observation was explained with the relative role of directivity of the fault rupture. It is dominantly observed in the magnitude of 7.0 and 7.1 for the case of most unfavorable values of structural parameters.

In the second phase of the sensitivity analysis, the influence of each structural parameter is investigated individually while all of the other parameters are kept constant at their central (average) values. Considering the results, strength ratio, period and ductility ratio seem to be more effective structural parameters on DS than others for URM structures.

Determination of the damage state probabilities for the URM buildings models in terms of PGA and magnitude for soft and hard soil conditions is the last study in this part. The assessment of performance level of structures is carried out by using the target limit states, which are identified by using the displacement capacity of the equivalent SDOF models. With this approach, the conditional probability of exceeding the predefined LS can be generated by determining the probabilities of being in a damage state at a predetermined PGA or magnitude value in accordance with the relationship between LS and DS. According to the results with changing PGA for both soil conditions as presented in Figure 3, it can be stated that

- The influence of soil conditions on the probability exceedance of the LS of interest does not seem to be significant with changing PGA. It should also be noted that different quantities of data at the same PGA value for both site conditions lead to the undesired trend in the interval of 0.7g and 0.8g.
- The recorded maximum PGA value is observed as 1.0g in soft soil conditions while it is reduced to 0.8g in hard soil conditions.

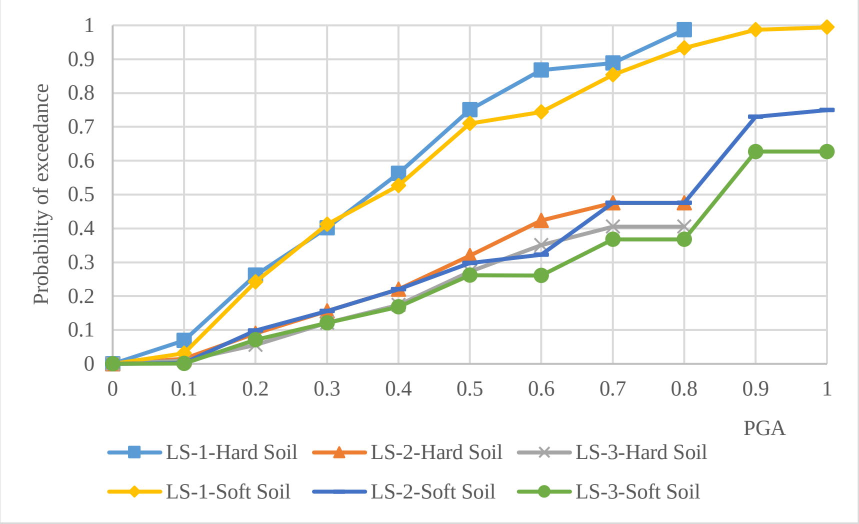

Figure 3. Comparison of LS with changing PGA values for both soil conditions

With changing moment magnitude values for both soil conditions, probability of exceedance of URM buildings for each LS shown as Figure 4 can be interpreted as follows:

- Considering the influence of soil conditions on the performance levels of structural simulations, it can be stated that except a slight difference for LS-1 the probabilities of other LS are nearly similar for both site conditions. Furthermore, the probability of exceedance of all boundaries of LS with changing the magnitude values in hard soil conditions has a tendency to reduce when compared with the case of soft soil conditions.
- URM models are slightly more vulnerable to simulated ground motions in soft soil conditions for all LS, especially for higher magnitudes. The differences seem to be at most 10% for magnitude value of 7.0.

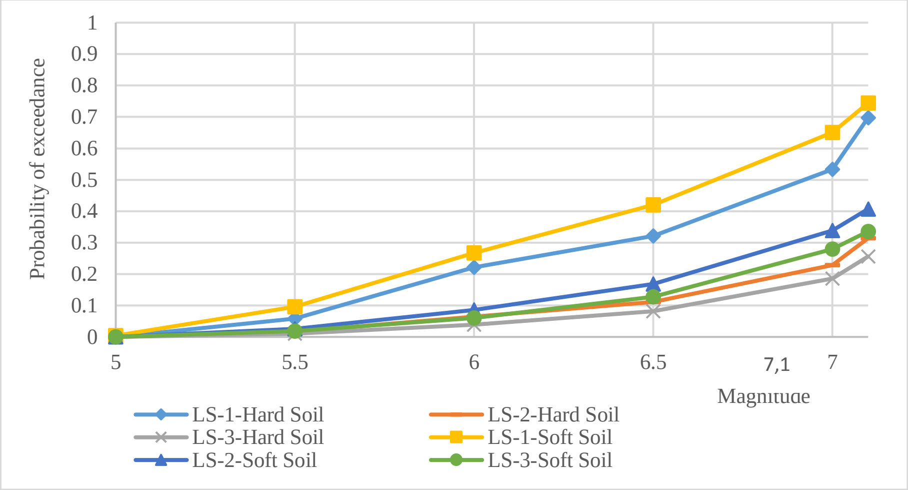

Figure 4. Comparison of LS with changing magnitude values for both soil conditions

4. LINEAR DISCRIMINANT ANALYSIS

The main purpose of this section is to determine the most effective seismological or structural parameters on damage state via this statistical method (linear discriminant analysis), which is carried out with the SPSS software. The relationships between the dependent variable (i.e. DS) and independent variables, consisting of seismological parameters, which are magnitude, soil condition and R_{JB} distance, and the structural parameters, namely period, strength ratio, ductility ratio, post-yielding ratio, post-capping ratio, residual strength ratio and hysteresis model degradation parameter are investigated. Linear discriminant analysis is a suitable statistical tool to determine effective independent variables on DS since the dependent variable is categorical in this study. The linear combination in an equation, which is a combination of several variables such that no variable is multiplied by either itself or another, is employed to represent the relationships between DS and independent variables by conceptualizing them in a simple way and conducting the calculations readily. In other words, a large amount of data, i.e. 2.430.000 distinct seismic response data in terms of displacement obtained after nonlinear dynamic analyses can be expressed with discriminant analysis by using the linear combination in order to explain the influences of each independent variable on DS in a simple manner. Linear discriminant analysis is a multivariate technique to classify the relative weights of independent variables between the groups of a case.

According to Table 4, three reasonable linear discriminant relationships are obtained. The first relationship should be selected as its eigenvalue is greater than 1.0 and the canonical correlation of the eigenvalue at the first relationship is the closest to 1.0. It is also observed that the first relationship has a 96.7% of the discriminating ability as far as three continuous discriminant relationships are considered. Dividing the eigenvalue of the relationship to the sum of all eigenvalues determines the percentage of variance.

Table 4. *Eigenvalues of the discriminant relationships*

Relationship of DS	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	1.299	96.7	96.7	0.752
2	.036	2.7	99.4	0.188
3	.008	0.6	100.0	0.087

Since the significance of the relationships obtained from the chi-square test, which is carried out to determine the discriminating ability of the relationships, is equal to 0.0, all of these three relationships extracted in the DA seem to be reasonable to interpret the relationships of the dependent variable (i.e. DS). However, one of them has the most accurate relationship when Wilks' lambda values are compared as given in Table 5. Accordingly, the first damage state relationship for the structural simulations seems more suitable than others.

Table **Error! No text of specified style in document.**. *Wilks' lambda values of the discriminant relationships*

Test of Relationship(s)	Wilks' Lambda	Chi-square	df	Significance
1 through 3	0.417	2128298.682	30	0.000
2 through 3	0.958	105484.680	18	0.000
3	0.992	18462.286	8	0.000

Considering Table 6, it is observed that the strength ratio, magnitude of the earthquake and source-to-site distance are the most effective parameters for the URM structures, respectively.

Table 6. *Coefficients of the independent variables for each discriminant relationship*

	Relationship 1	Relationship 2	Relationship 3
Magnitude (M_w)	-.687	.367	-.100
Soil (S)	.141	.126	-.046
Distance (R_{JB})	.513	-.081	-.017
Period (T)	.105	.632	.452
Strength Ratio (η)	.812	.444	-.133
Ductility Ratio (μ)	.027	.320	-.683
Post-yielding Ratio (α_s)	.001	.111	.171
Post-capping Ratio (α_r)	.003	.057	.488
Residual Strength Ratio (λ)	-.015	-.089	-.139
Degradation Parameter (γ)	.006	.033	.071

Period is also known as an important structural parameter for the identification of seismic behavior during an earthquake excitation. However, the strength ratio of URM structures is observed to dominate its influence in this study. The influences of other structural parameters, namely ductility, residual strength ratio, post-yielding ratio, post-capping ratio and hysteresis model degradation parameter do not appear to be significant for the URM structures.

According to Table 7, 77.5% of DS-1 is correctly classified, whereas this percentage is 56.3%, 53.6% and 68.2% for DS-2, DS-3 and DS-4, respectively. Totally, 71.7% of original grouped cases is correctly classified. It is observed that the DS-1 and DS-4 are better classified due to their more certain nature as compared to the intermediate damage states.

Table 7. *Classification of the results between the groups of DS*

			Predicted Group Membership				Total
		DS	1.00	2.00	3.00	4.00	
	Count	1.00	1252896	269369	72578	22220	1617063
		2.00	20975	256936	120661	57867	456439
		3.00	0	17454	39878	17000	74332
		4.00	2	22010	67618	192536	282166
	%	1.00	77.5	16.7	4.5	1.4	100.0
		2.00	4.6	56.3	26.4	12.7	100.0
		3.00	0.0	23.5	53.6	22.9	100.0
		4.00	0.0	7.8	24.0	68.2	100.0

5. CONCLUSIONS

Considering all the limitations and simplifications employed in this study, the following conclusions can be drawn from the results of seismic performance analysis of URM structures:

- The strength ratio seems to be the most effective independent variable, which affects the DS of URM structures; hence, it should be majorly considered in seismic design and assessment of URM structures. In addition, the strength ratio leads to an increased effect of fundamental period, which is the second most effective structural parameter.

- The earthquake magnitude is found to be the second most effective independent variable that determines DS of URM structures. Seismic damage initially begins to appear around M_w=5.5 for URM structures. In general, DS decreases with higher performance values of the structural parameters. For instance, the mean value of DS for the lowest performance values of the structural parameters with the M_w=7.1 is 3.85 and it is 1.78 for the same earthquake when the highest performance values are used.
- Source-to-site distance is the third most effective variable on the DS-score of URM structures. As expected, source-to-site distance highly affects performance level of the URM structures. In this study, the effect of R_{JB} distance becomes pronounced with M_w=6.0.
- Soft and hard soil conditions have the same mean DS values for M_w=5.0 and 5.5. The influence of site condition begins to increase with M_w=6.0 and slight differences are observed with changing magnitudes.
- The fault rupture directivity effects lead to the occurrence of higher DS values at dummy stations far from the fault plane. In this study, the variation of mean DS values at different R_{JB} distance intervals demonstrated directivity effects under the same earthquake magnitudes.
- Ductility is an essential structural parameter to represent the displacement capacity of structures and the capability of absorption of earthquake energy. However, URM structures represent brittle behavior under seismic excitations. According to the numerical results in this study, URM structures have tendency to be in DS-1, DS-2 and DS-4. Thus, the effect of ductility for URM structures is observed to be less than the effects of the strength ratio and fundamental period.
- Other structural parameters as the post-yielding ratio, post-capping ratio, residual strength ratio, and degradation parameter are found to be non-effective variables on the DS of URM structures. For instance, even though higher degradation parameter enables to absorb more energy in a hysteretic curve, a URM structure has lower energy absorption capacity due to its material characteristic and thus its DS value is not affected by this parameter.
- Furthermore, strength seems to be the most important structural parameter for rigid and brittle URM structures. If the capacity is not exceeded during ground shaking, the building survives without severe damage. However, if the capacity is exceeded, then the structure generally gets heavy damage or collapses since the safety margin in the inelastic range is narrow due to limited ductility and energy dissipation capacity. This means URM structures should be designed or evaluated by using force-based approaches and sufficient force capacity should be ensured in all the cases rather than the displacement capacity.
- Finally, the results of this study verify that URM structures are under high seismic risk even in the case of moderate ground motion intensities. Therefore, new masonry buildings should be constructed according to the current seismic regulations and the existing masonry buildings should be retrofitted to enhance their strength and displacement capacity.

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