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RELIABILITY-BASED SEISMIC ASSESSMENT OF ASYMETRIC MULTI-STOREY BUILDINGS WITH RC SHEAR WALLS

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ABSTRACT

The performance of buildings subjected to earthquake loads has shown that asymmetric structures are caused more extensive damages in comparison with symmetric structures. Hence, the seismic performance of asymmetric structures should be assessed due to future random earthquakes. Reliability-based seismic assessment as one of the tools in performance-based earthquake engineering has been introduced to quantify the seismic reliability for existing structures due to future random earthquakes. This paper deals with the reliability-based seismic assessment of asymmetric multi-storey buildings with RC shear walls with consideration of the angle of ground motion incidence. To implement this purpose, in the first stage, the multi-component incremental dynamic analysis (MIDA) is used for the assessment of asymmetric 6 and 9-storey buildings with RC walls. The MIDA as an efficient procedure can estimate the seismic capacity of a structural system with randomness on incident angle. In the second stage, the mean annual frequency exceeding of a specified level of structural demand is calculated to predict the reliability of these structures. The results show that the effects of earthquake incident angle should be considered in the assessment of the assessment of asymmetric multi-storey building.

Keywords: Asymmetric multi-storey buildings; shear wall; seismic assessment; reliability; multi-component incremental dynamic analysis.

1. INTRODUCTION

Ductile buildings have been introduced as reliable resistant structures subjected to earthquake loads in accordance with the seismic building codes. These structures have an

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ability of withstanding large inelastic deformations without considerable degradation in strength and stiffness. RC shear walls in multi-storey buildings have been proposed as one of the ductile lateral load resisting systems in the seismic building codes. Non-uniform distribution of mass, stiffness and strength are caused asymmetrical in multi-storey buildings. Tensional moments and rotational deformations have been recognized as the danger of excessive rotational response in asymmetric structures. Rotational deformations cause non-uniform distribution demand in lateral force resisting elements. Consequently, it leads to increase damages in an asymmetric building. These effects have been confirmed in the past earthquake such as Mexico City 1986 [1].

The seismic performance of a structure during an earthquake depends on its seismic responses and its capacity that both of them are inherently uncertain. Hence, the effect of theses uncertain parameters should be considered in the seismic performance prediction of structures. Recently, reliability-based seismic assessment has been introduced as an efficient process in Performance-Based Design (PBD) to quantify the seismic reliability of existing structures due to future random earthquakes [2]. In this procedure, the quantification is represented by confidence level or the probability to satisfy the desired performance at discrete hazard levels. Furthermore, the mean annual frequency (MAF) of exceeding a specified level of structural demand is estimated in this procedure. Two probabilistic formats namely, Engineering Demand Parameter (EDP)-based approach and Intensity Measure (IM)-based approach have been proposed for reliability-based assessment of performance levels of the structural systems [3].

It has been shown that in actual buildings the seismic assessment may lead to different results from those single-storey models [4]. Furthermore, the selection of an appropriate time history record [5] and the influence of the angle of ground motion incidence on demand parameters for an asymmetric multi-storey building subjected to bi-directional ground motions. Therefore, the influence of the earthquake incident angle on realistic building should be considered.

This study aims to investigate the reliability-based seismic assessment of asymmetric multi-storey buildings with RC shear walls with consideration of the angle of ground motion incidence. In order to realistically assess the seismic behavior of asymmetric multi-storey building with RC walls, 3-D 6 and 9-storey buildings with influence of the earthquake incident angle are considered in this paper. To achieve this purpose, in the first stage, the multi-component incremental dynamic analysis (MIDA) [6] is used for the assessment of asymmetric multi-storey building according to PBD. MIDA is considered as an efficient procedure which can estimate the seismic capacity of the structural system with randomness on incident angle. Buildings are designed according to the Iranian Seismic Code 2800 [7] and ACI 318-05 [8]. Analytical models of the 3-D buildings are developed using SeismoStruct software [9] which is known as nonlinear finite element program and is capable of performing nonlinear static and dynamic analyses. Furthermore, a robust and detailed analytical model is given in which beams, columns and shear walls are modeled to simulate the actual behavior of these buildings as accurately as possible. Finally, according to the results of MIDA, the mean annual frequency exceeding of a specified level of structural demand is calculated to predict the reliability of these structures. The results of MIDA show that the earthquake incident angle significantly affects the seismic assessment. Hence, the effects of earthquake incident angle should be considered in the assessment of the assessment of asymmetric multi-storey building.

2. DESIGN OF STRUCTURES

To evaluate the performance of asymmetric multi-storey buildings with RC shear walls, 6 and 9-storey buildings are designed for a site (Kerman, Iran) which represents a high seismic zone. These buildings assumed to be located on soil type B (Average shear wave velocity to a depth of 30 m would be 360-750 m/s). The buildings are similar in plan and consist of five bays in each direction and the storey heights of buildings are 3.2 m. the plan of buildings consists of four walls in *x* direction and three walls in *y* direction. These walls are depicted by using W*i* label in plan, shown in Figure 1. Also, 3-D view of 6-storey building is shown in Figure 2.

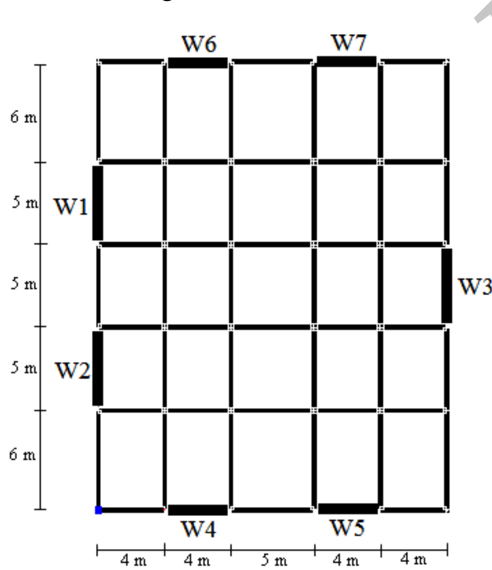

Figure 1. Plan view of buildings

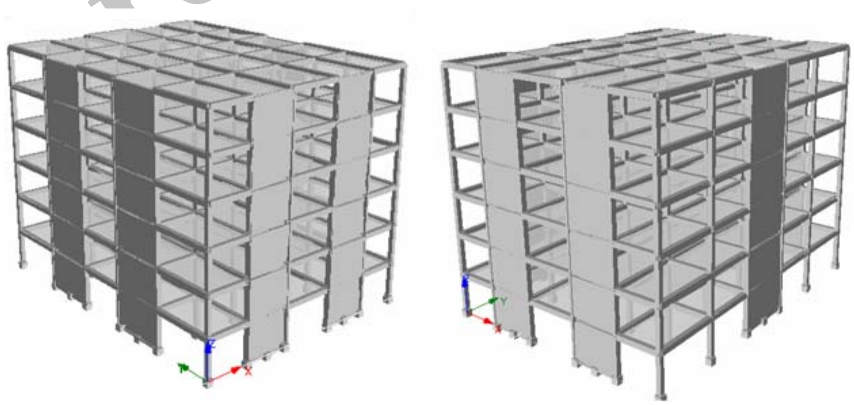

Figure 2. 3-D view of 6-storey building

A rigid diaphragm can be assumed according to the floor deck ceiling system existing in usual structures. Gravity loads are supposed to be similar to common residential buildings in Iran [10]. These buildings are loaded and designed according to the Iranian Seismic Code 2800 [7] and ACI 318-05 [8]. The cross-section areas and the diameter of longitudinal bars for beams and columns of these buildings are shown in Tables 1 and 2. The members of 6 and 9-storey buildings are divided into two and three groups in the height of structure, respectively.

Table 1: The properties of cross-section areas for 6 and 9-storey building

Building	Section	Section type	Section dimension (m)	Reinforcement(mm)		
				top-bottom	Left-right	Corners
6-storey						
	Column	1	0.40×0.40	4Φ20	4Φ20	4Φ20
	Column	2	0.40×0.40	4Φ16	4Φ16	4Φ16
	Beam	1	0.45×0.40	8Φ22	-	-
	Beam	2	0.40×0.40	8Φ20	-	-
9-storey						
	Column	1	0.50×0.50	4Φ25	4Φ25	4Φ25
	Column	2	0.50×0.50	4Φ22	4Φ22	4Φ22
	Column	3	0.50×0.50	4Φ18	4Φ18	4Φ18
	Beam	1	0.50×0.40	8Φ28	-	-
	Beam	2	0.50×0.40	8Φ25	-	-
	Beam	3	0.50×0.40	8Φ20	-	-

The cross-section of shear wall is depicted in Figure 3. The cross-section areas and the diameter of longitudinal bars for wall of these buildings are shown in Tables 3 and 4.

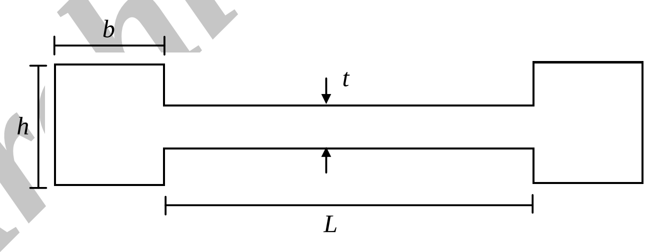

Figure 3. The Cross-section of shear wall

3. ANALYTICAL MODELS OF THE 3-D BUILDINGES

Analytical models of the 3-D buildings depicted in Figures 1 and 2 is established using SeismoSrtuct software, a structural analysis software framework specialized for nonlinear analyses [9]. Beams and columns of the structures are modeled using force-based nonlinear beam-column element that considers the spread of plasticity along element's length. The integration along each element is based on Gauss-Lobatto quadrature rule. Kent-Scott-Park model [11] is used as the confined and unconfined concrete constitutive model. The concrete of cover and core in cross-section of the columns is considered as unconfined and confined, respectively. The stress-strain relationships for confined concrete are adopted from Saatcioglu and Razvi [12]. The ultimate compressive strain of confined concrete introduced by Paulay and Priestley [13] is considered. Constitutive behavior of the reinforcing steel is based on using the one-dimensional J_2 plasticity model with linear hardening. The material damping matrix of the buildings is constructed by using the Rayleigh method [14]. The factor of proportionality for damping matrix of building is computed by assuming 5% viscous damping. The $P-\Delta$ effects are considered in nonlinear time historey analysis.

Table 2: The properties of cross-section areas of shear wall for 6 and 9-storey building

Building	Wall	Section Dimensions (m)				Reinforcement (mm)			
		L	t	h	b	Column Corners	Column Top-bot	Column Left-right	Wall Middle
6-storey									
	1, 2	5.45	0.30	0.45	0.45	4Φ20	6Φ20	6Φ20	46Φ20
	3	5.45	0.30	0.45	0.45	4Φ22	6Φ22	6Φ22	60Φ22
	4, 5, 6, 7	4.45	0.30	0.45	0.45	4Φ20	4Φ20	4Φ20	36Φ20
9-storey									
	1, 2	5.45	0.30	0.50	0.50	4Φ20	6Φ20	6Φ20	46Φ20
	3	5.45	0.30	0.50	0.50	4Φ22	6Φ22	6Φ22	60Φ22
	4, 5, 6, 7	4.45	0.30	0.50	0.50	4Φ20	4Φ20	4Φ20	36Φ20

4. MULTI-COMPONENT INCREMENTAL DAYNAMIC ANALYSIS

The incremental dynamic analysis (IDA) approach is an efficient tool for seismic evaluation of structures to define a curve through a relation between the seismic intensity level and the corresponding maximum seismic response of structure [15]. An intensity measure (IM) and an engineering demand parameter (EDP) are used as the intensity level and the structural response, respectively. Selecting IM and EDP is one of the most important steps of the IDA approach. The IM parameter has been considered as a monotonically scalable ground motion intensity measure like the peak ground acceleration (PGA), peak ground velocity (PGV), the ξ = 5% damped spectral acceleration at the structure's first-mode period ($Sa(T_1$, 5%)) and many others. The damage of structures can be quantified by using any of the EDPs. The values of particular structural damage states are used as the EDPs. Ghobarah *et al*. [16] classified the EDPs into four categories. The categories are engineering demand parameters based on maximum deformation, engineering demand parameters based on cumulative damage, engineering demand parameters accounting for maximum deformation and cumulative damage, global engineering demand parameters.

Multi-component incremental dynamic analysis (MIDA) was proposed by Lagaros [6] to consider the impact of the earthquake incident angle on the seismic loss estimation. In fact, MIDA as straightforward procedure is based on the idea of considering variable incident angle for each record, taking into account randomness both on the seismic excitation and the incident angle. Consequently, the MIDA procedure can be used as an efficient tool for seismic assessment of 3-D structures. In the MIDA procedure, a structure subjected to the simultaneous action of two orthogonal horizontal ground accelerations along the directions *x* and *y* is illustrated in Figure 3.

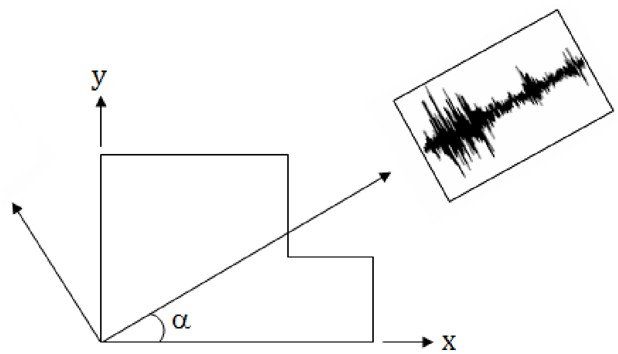

Figure 3. Definition of the incident angle α

To assess seismic reliability of 3D buildings, first, MIDA is performed in a similar as the way 2-D implementation of IDA, i.e. a suit of records is selected and for each record an MIDA representative curve is derived. A schematic representation of MIDA procedure is shown in Figure 4. Then, by using the results of MIDA curves the seismic reliability of 3-D buildings are evaluated according to FEMA guidelines [17] and PBD approach.

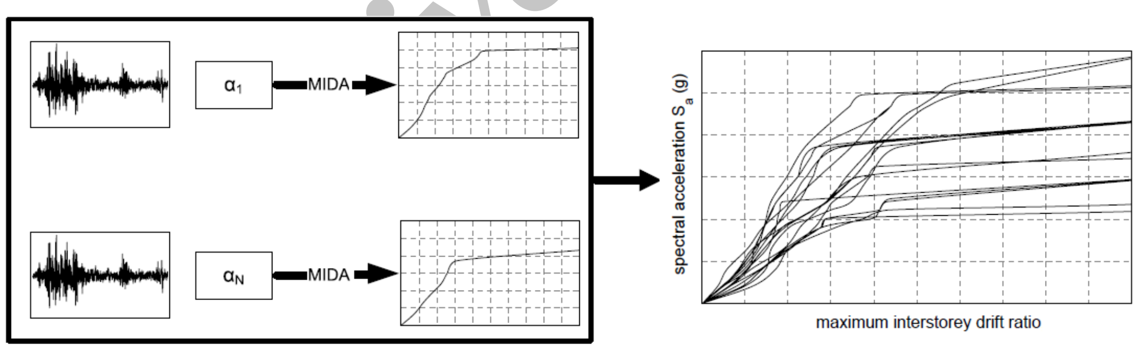

Figure 4. The MIDA procedure

4.1 Performing MIDA

In order to perform the MIDA procedure, a set of ground motion records and a set of incident angles for each recode should be selected. In this study, three recodes are selected, which the characteristics of these records are shown in Table 5 [18]. The selected ground motions are effectively presumed to be representative of events likely to cause severe ground motions in the site on which structures are located. Selection of a suitable intensity measure and damage measure is the most important issues for performing a MIDA.

Table 5: The suite of three ground motion records

Record Station	Duration (sec)	Specific Energy Density(cm2/sec)	Arias Intensity (m/sec)	Effective Duration (sec)
Imperial Valley (M=6.5)	63.72	21515.904	42.777	29.71
Loma (M=6.9)	39.64	22382.255	17.436	18.18
Northridge (M=6.7)	35.96	14280.841	20.235	21.68

In the present study, the Sa (T_1, 5%) is selected as the IM parameter. Furthermore, the maximum inter-storey drift (θ_{max}) and the diaphragm rotation are selected as the EDPs which are based on the maximum deformation. The reason of selecting θ_{max} is that the performance levels in PBD approach have been described by using inter-storey drift values. To consider the impact of the earthquake incident angle on the seismic loss estimation, the values of $0^{\circ}, 10^{\circ}, 45^{\circ}, 90^{\circ}, 135^{\circ}, 165^{\circ}$ and 180° are selected as incident angles for each record. Once the model of the buildings has been formed and the ground motion records with incident angles have been selected, for performing the real nonlinear dynamic analyses required for MIDA, each record is scaled to cover the entire range of structural response, from elasticity, to yielding, and finally collapse. The non-linear time history analysis is performed and the maximum inter-storey drift value is obtained. The ground motion is then incrementally increased and the analysis repeated until numerical non-convergence is encountered. MIDA curves using all records for buildings are obtained. All MIDA curves for 6-storey and 9-storey buildings are shown in Figures 5 and 10.

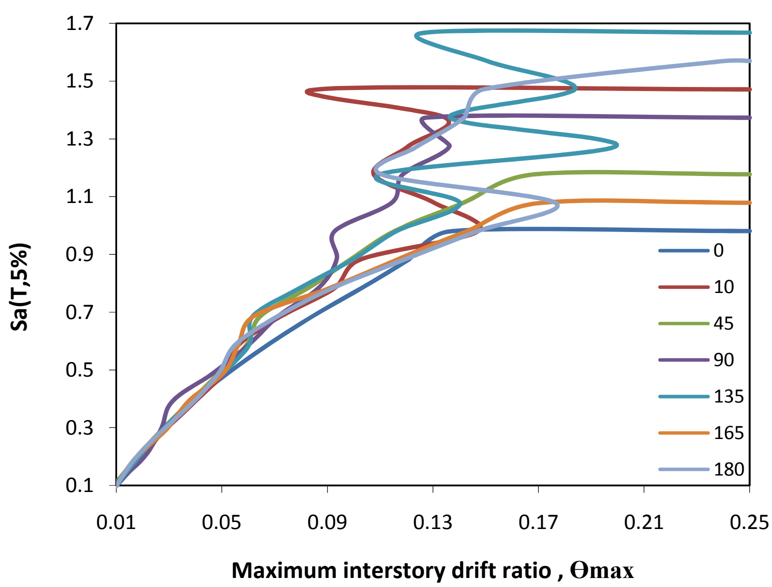

Figure 5. MIDA curve of 6-storey building for Imperial Valley

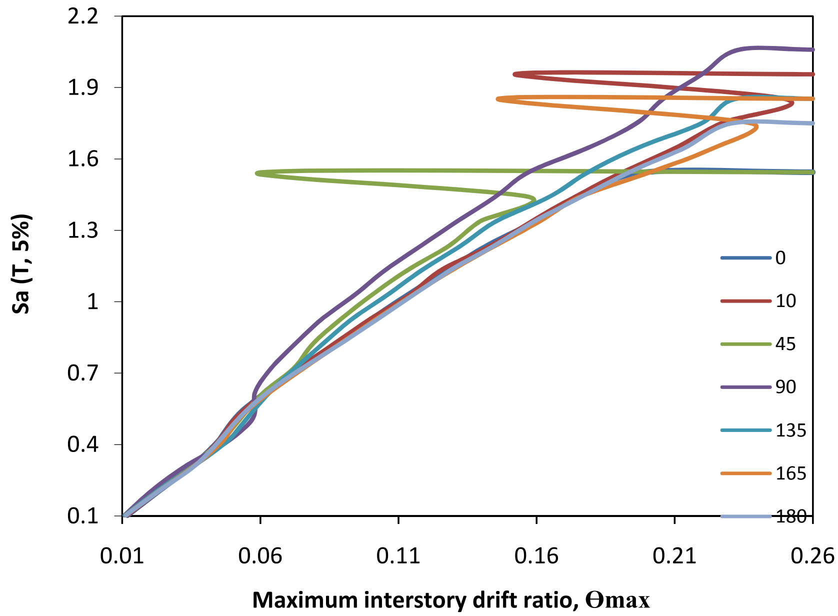

Figure 6. MIDA curve of 6-storey building for Loma

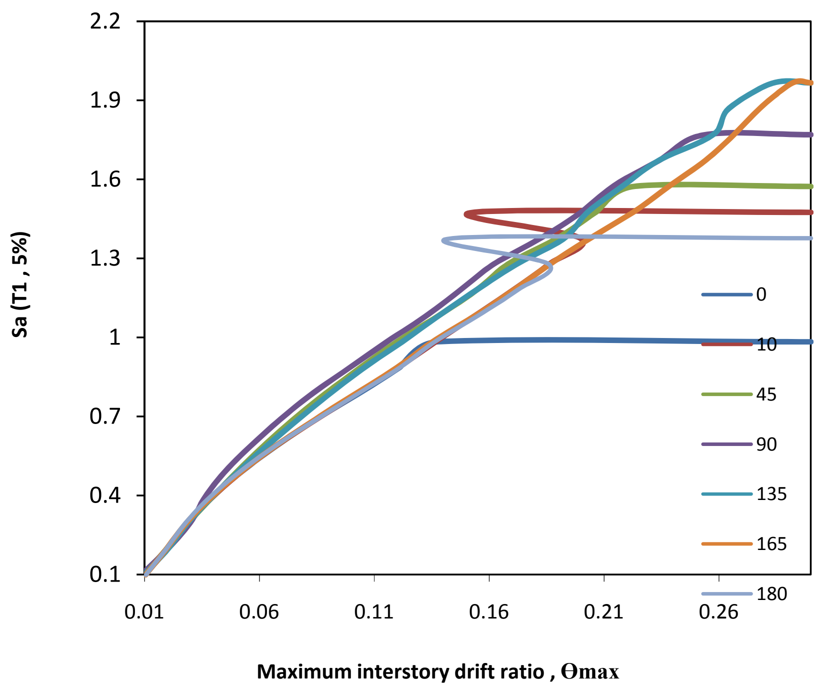

Figure 7. MIDA curve of 6-storey building for Northridge

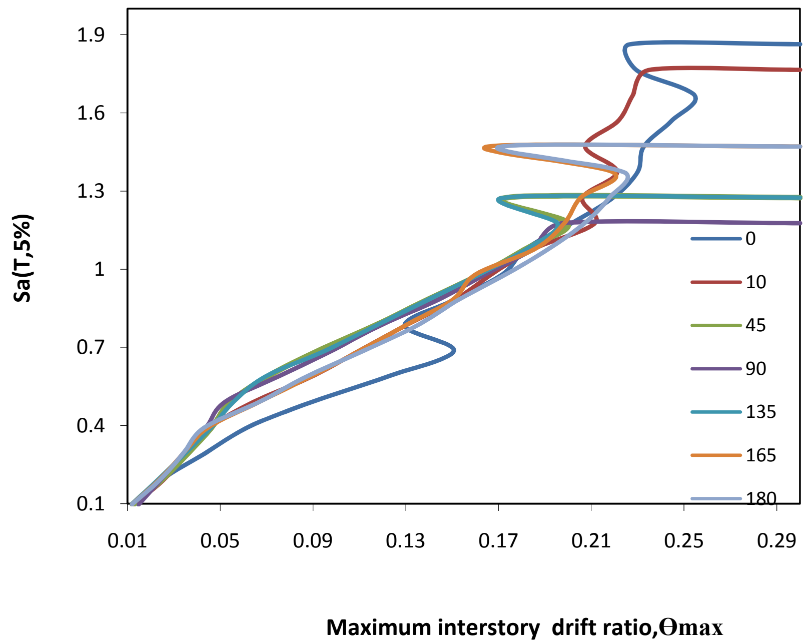

Figure 8. MIDA curve of 9-storey building for Imperial Valley

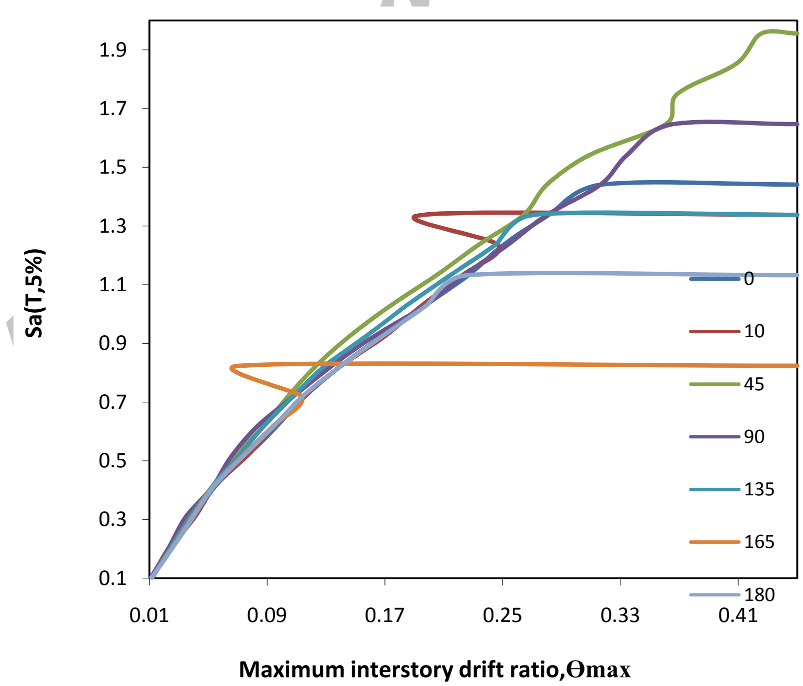

Figure 9. MIDA curve of 9-storey building for Loma

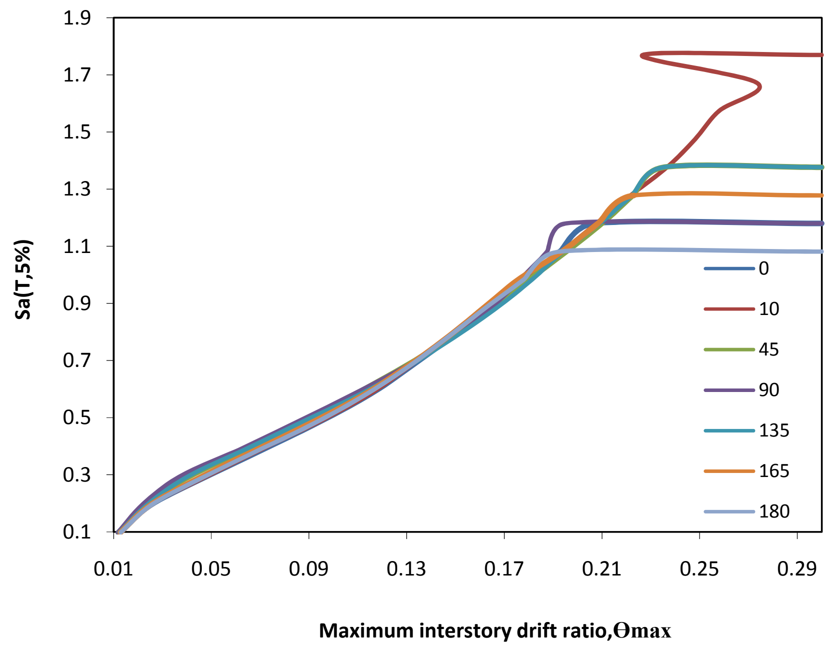

Figure 10. MIDA curve of 9-storey building for Northridge

Figures 5 to 10 shows that the earthquake incident angle affects on the maximum inter-storey drift value. Therefore, the effects of the earthquake incident angle should be considered in the assessment of asymmetric multi-storey building.

5. RELIABILITY-BASED SEISMIC ASSESSMENT

Reliability-based seismic assessment of buildings involves the estimation of a level of confidence that a structure will be able to achieve a desired performance objective as outlined in FEMA-350 [17]. In this paper, based on the study done by Cornell *et al*. [19], a seismic reliability assessment is provided in a probabilistic framework for all structures.

5.1 Definition of limit states on MIDA curves

In order to assess the seismic reliability of buildings, limit-states on the MIDA curves should be defined. Three limit states are considered namely Immediate Occupancy (IO), Collapse Prevention (CP) based on FEMA [17], and global dynamic instability (GI). For The IO limit-state is defined as $\theta = 1\%$ for. As for CP point two criteria are to be met. The first one simply involves a local tangent of the IDA curve which is not to be less than 20% of the initial elastic slope. If this local tangent becomes less than 20% of the initial slope, CP is violated. The second criterion is defined as $\theta = 10\%$ for asymmetric multi-storey buildings with RC walls. The second criterion is occurred for 6-storey and 9-storey buildings for all recodes subjected incident angles.

5.2 Seismic reliability assessments

As noted earlier, the seismic reliability assessment of present structures is performed based on research done by Cornell *et al*. [19]. Recent performance based guidelines [17] propose a scheme for assessing the mean annual frequency or annual probability of exceeding a limit state for a given structure at a designated site. This scheme de-convolves the assessment by introducing DM and IM in an integral form as the equation below [19]:

$$\lambda[LS] = \iint_{DM,IM} G[LS / DM]|dG[DM / IM]||d\lambda[IM] \tag{1}$$

where $\lambda[LS]$ is the mean annual frequency of exceeding the limit state LS and $G[LS/DM]$ denotes the probability of exceeding the LS given the value of DM and finally $G[DM/IM]$ denotes the probability of exceeding each value of DM given the value of IM.

By using probabilistic seismic hazard analysis Cornell [19], one could explicitly obtain the term $\lambda[IM]$ which is in other words the hazard curve of a given site. This value of $\lambda[LS]$ is directly obtained if one tries to evaluate each term explicitly and solves for the results using any numerical integration method. The first approximation involves the hazard curve which can be considered as a simple exponential function of S_a. The second approximation involves the estimation of IDA median curve which again can be defined as equation below [19]:

$$\hat{D} = a(S_a)^b \tag{2}$$

This simplification is consistent with the equal displacement rule [19] for moderate period structures. Values of a and b can be estimated by IDA using statistical calculations [19]. It suffices to state that one could conduct a regression analysis of Log normally distributed values of demand and intensity measure and then find the dispersion of the variables to get the values of a and b. Using these assumptions and simplifications, a double integral of the performance based assessment would turn into a straightforward equation as follows [19]:

$$P_{PL} = H(S_a^{\hat{C}}) \exp\left[\frac{1}{2}\frac{k^2}{b^2}(\beta_{D/S_a}^2 + \beta_C^2)\right] \tag{3}$$

Where $H(S_a^{\hat{C}})$ is the approximated hazard curve in the range of spectral accelerations in the region of probabilities around the limit state probability. $\hat{C}$ is the median of drift capacity and k is a logarithmic slope of the approximated hazard curve which is reported as 1.5 to 3 by Cornell *et al* [19]. β_{D/S_a} and β_C are the dispersion of drift demands and that of drift capacity respectively. Finally, P_{PL} is the annual probability of the performance level which is the primary purpose of seismic reliability assessment.

Eq. (3) incorporates both site and structure specific characteristics in simple manner which is readily calculated using relevant data. In this study, the probabilistic seismic hazard is selected based the site and the relevant hazard curve shown in Figure 10, Ref. [21].

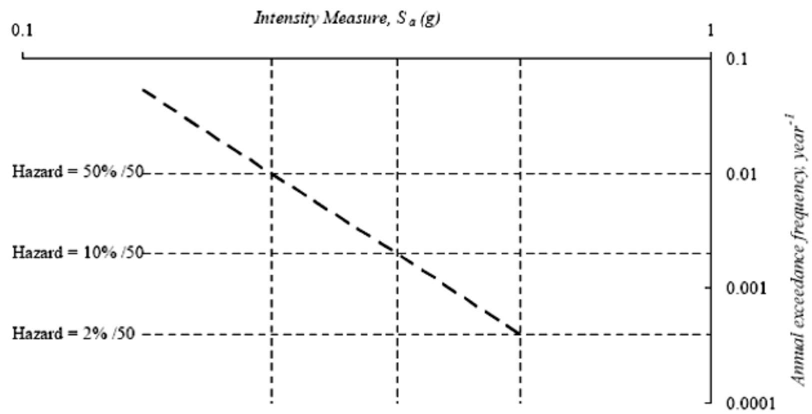

Figure 10. Seismic hazard curve [21]

Moreover, it is feasible to set the P_{PL} equal to any performance objective (e.g. 50% or 2% in 50 years) and rearrange the Eq. (3) to confirm whether existing buildings meet any performance objectives denoted by P_0. Rearranging Eq. (3) yields [19]:

$$\left\{\exp\left[-\frac{1}{2}\frac{k}{b}\beta_C^2\right]\right\}\hat{C} \geq \left\{\exp\left[\frac{1}{2}\frac{k}{b}\beta_{D/S_a}^2\right]\right\}\hat{D}^{P0} \tag{4}$$

Or the Eq. (4) can be shown as follows:

$$\varphi\hat{C} \geq \lambda\,\hat{D}^{P_0} \tag{5}$$

Therefore, seismic reliability assessments of 6 and 9-storey buildings are calculated based on Eqs. (1) to (5) and shown in Tables 6 and 7.

Table 6: Calculation of the annual probability for 6-storey buildings

S_a	$H_D(d)$	P_{PL}	ϕ	γ	λ	k	$C.L$
0.103	44.6743	0.1077	0.9994	1.00183	0.09739	20.1170	0.999
0.206	6.7338	0.1077	0.9994	1.00195	0.19416	13.8349	0.999
0.309	2.2262	0.1078	0.9994	1.00218	0.29182	9.96597	0.999
0.412	1.0149	0.1077	0.9994	1.00189	0.38993	8.04634	0.999
0.513	0.5516	0.1077	0.9994	1.00047	0.48990	9.34548	0.999
0.618	0.3353	0.1077	0.9994	1.00075	0.59008	6.15329	0.999
0.721	0.2202	0.1077	0.9994	1.00179	0.70717	3.03595	0.998
0.823	0.1529	0.1077	0.9994	1.00170	0.85888	1.371811	0.914
0.926	0.1109	0.1078	0.9994	1.00224	1.00593	-0.02468	0.492

Table 7: Calculation of the annual probability for 9-storey buildings

S_a	$H_D(d)$	P_{PL}	ϕ	γ	λ	k	$C.L$
0.103	44.6764	0.3051	0.9986	1.00144	0.12188	19.7719	0.999
0.206	6.7307	0.3049	0.9986	1.00048	0.24396	16.4004	0.999
0.309	2.2283	0.3054	0.9986	1.00350	0.39331	6.6663	0.999
0.412	1.018	0.3060	0.9986	1.00757	0.56014	3.0862	0.999
0.515	0.5538	0.3061	0.9986	1.00855	0.75589	1.4419	0.925
0.618	0.3363	0.3058	0.9986	1.00670	0.96428	0.2449	0.594
0.721	0.2205	0.3055	0.9986	1.00410	1.16696	-0.9991	0.161

The results of Tables 6 and 7 are shown that the 50% in 50 year hazard are obtained in S_a=0.92 and 0.6 for 6 and 9-storey buildings, respectively.

6. CONCLUSIONS

In this paper, the reliability-based seismic assessment of asymmetric multi-storey buildings with RC walls is considered with the angle of ground motion incidence. To achieve this purpose, the multi-component incremental dynamic analysis (MIDA) is used for the assessment of asymmetric multi-storey buildings with RC walls. MIDA is introduced as an efficient procedure which estimates the seismic capacity of a structural system with randomness on incident angle. In order to predict the reliability of these structures, the mean annual frequency of exceeding a specified level of structural demand is estimated in this procedure. The results of MIDA show that the angle of ground motion incidence effect the seismic assessment of asymmetric multi-storey buildings with RC walls. Also, the critical angle of ground motion incidence is not predictable, and the set of angle should be considered in seismic assessment.

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