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Influence of Real Ground Motion Records in Performance Assessment of RC Buildings

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PAPER INFO	ABSTRACT
	Reinforced concrete frame buildings with Open Ground Story (OGS) are one of the most common building configurations in urban habitat. These configurations are known to be vulnerable to seismic excitations, primarily due to the sudden loss in strength in the ground story and differential stiffness distribution throughout the structure. The differential stiffness distribution is attributed primarily to the interaction of non-structural infill wall with the moment-resisting frame. Hence, the interaction of infill wall needs to be accounted in estimating the seismic vulnerability. Therefore, the present investigation is focused on understanding the impact of utilizing real ground motion records on the performance assessment of RC buildings with and without consideration of infill walls. Fragility curves were developed for low and mid-rise structural models using Capacity Spectrum Method (CSM) specified by ATC-40 and with Incremental Dynamic Analysis (IDA). CSM uses the response spectrum specified by the respective code, unlike IDA where an ensemble of spectrum compatible real ground motion accelerograms satisfying the necessary site conditions is used in assessing the performance. Further, significant variations observed in the developed fragility curves by CSM and IDA emphasizes the sensitivity of real ground motion data in performance assessment. *doi*: 10.5829/ije.2019.32.12c.07

NOMENCLATURE

W_{ds}	Equivalent width of the diagonal strut	L_{ds}	Length of the diagonal strut
E_m	Modulus of elasticity of masonry	E_c	Modulus of elasticity of concrete
I_c	Moment of inertia of concrete member	h	Height of the wall
t	Thickness of the infill wall	θ	Angle of the diagonal strut with the horizontal
D	Damage state	Φ	Standard normal cumulative distribution (CDF)
BF	Bare Frame	OGS	Open Ground Story
μ	Mean parameter for the natural logarithm of PGA	σ	Standard deviation parameter for the natural logarithm of PGA
P	Conditional probability of being in, or exceeding, a particular damage state (dsi)	S_d	Spectral displacement
β_{dsi}	Standard deviation of the natural logarithm of the displacement threshold	$\overline{S}_{d,ds_i}$	spectral displacement threshold

1. INTRODUCTION

Earthquakes are one of unavoidable devastative natural hazards that has the potential to cripple the economy of a nation. Hence, precise assessment of the performance of structures for these events is imperative to mitigate the risk and subsequent loss. Significant advancement in development of methodologies for vulnerability assessment has been reported [1-7]. Most of these

analyses are being carried out on a bare moment-resisting frame subjected to seismic forces, neglecting the contribution of non-structural infill wall. The infill wall contributes for increase in stiffness of the structure and plays a critical role in performance of reinforced concrete (RC) building structures, which are a common sight in urban habitat. During the past seismic events i.e., Latur (1993), Jabalpur (1997), Bhuj (2001) and Indonesia (2004), it has been established that the failure of these

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non-structural infill walls is the primary source of casualties, owing to sudden change in mass and stiffness characteristics in the ground story. In general, the prevalent design practices tend to ignore the influence of the infill stiffness in the upper stories of the building, thereby paving the way for the disaster. The ground story columns need to be specifically designed for increased bending moments and shear forces to remain functional. Further, different approaches for modelling the infill wall contribution has been reported in literature, and it has been found that modelling the infill wall as strut action gives sufficiently accurate results. Hence, in this investigation, infill wall contribution is modelled as a diagonal strut member as per IS 1893 (Part 1): 2016 [8].

Several approaches have evolved in developing the seismic fragility curves for a given intensity measure with respective advantages and limitations [9-11]. In this study Capacity Spectrum Method (CSM) specified by ATC-40 [12] and Incremental Dynamic Analysis (IDA) developed by Cornell [13] has been used for developing the fragility curves. CSM approach is simple to implement and gives sufficiently accurate results in case of regular structural configurations. An attempt has been made in this work to understand the influence of real earthquake ground motion records in predicting or assessing the damage characteristics of a structure. This is carried out by selecting several ground motion data as per the characteristics of the chosen site. Further, seismic vulnerability assessment of the structural models is modelled with and without infill and analyzed using CSM, and IDA approaches [13, 14]. Seismic vulnerability of a structure is defined as proneness to damage under seismic excitation for a given intensity measure [1, 15-20]. It is expressed as a relationship between intensity measure and damage measure. Moreover, fragility curves developed using both CSM and IDA approaches clearly depict the performance of the structural models for various limit states. The variability of the fragility curves pronounces the influence of real ground motion record in assessing the behavior of the structure.

2. STRUCTURAL MODEL

Regular and symmetrical RC ordinary moment resisting frame models (OMRF) with and without infill walls located in seismic zone III [8], as depicted in Figure 1 were considered for assessing the seismic performance. These configurations are modelled as regular with low-rise (3 stories) and mid-rise (6 stories), which are also referred as G+2 (Ground + 2 stories) and G+5 (Ground + 5 stories) respectively, consisting of five bays in the X and Y directions. Finite element modelling of the geometry (column, beam and roof diaphragm) and seismic analysis of these structural models are carried out

using SAP2000 [21]. Plastic hinge behavior of structural members i.e., beams (M3 hinges) and columns (P-M2-M3 hinges) are defined as per FEMA 356 [22]. Reinforced concrete degradation behavior under cyclic, loading is modelled using Takada hysteresis model depicted in Figure 2 [23]. Further, the stress-strain behavior of confined concrete is modelled using Mander material model [24]. The geometrical and material characteristics for the structural models are shown in Table 1.
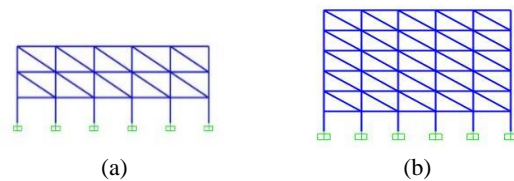

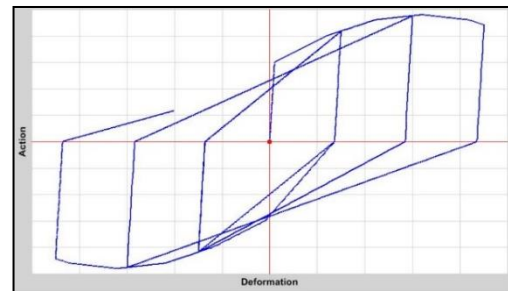**Figure 1.** Typical Elevation of (a) Low-rise (b) Mid-rise OGS frames

Figure 2. Takeda Hysteresis Model

TABLE 1. Model Properties

Parameter	Units	Data
Height of each story	[m]	3
Width of each bay	[m]	5
Grade of concrete	-	M 30
Poisson ratio of concrete	-	0.2
Unit weight of concrete	[kN/m^3]	25
Modulus of elasticity of concrete	[MPa]	27386
Modulus of elasticity of rebar	[GPa]	200
Grade of rebar	-	Fe 415
Beam width	[m]	0.23
Beam depth	[m]	0.45
Column width	[m]	0.3
Column depth	[m]	0.6
Thickness of infill wall	[m]	0.23
Modulus of elasticity of infill	[MPa]	13800
Unit weight of infill	[kN/m^3]	17.65
Poisson ratio of infill	-	0.17

Interaction of infill wall with the RC frame is modelled as 'equivalent diagonal strut' using empirical equations given below as per IS 1893 (Part 1): 2016 [8] in which, the ends of the diagonal strut are pin-jointed with the RC frame and the thickness and modulus of elasticity of the equivalent strut are the same as that of the infill.

$$W_{ds} = 0.175\alpha_h^{-0.4} L_{ds} \tag{1}$$

$$\alpha_h = h\left(\sqrt[4]{\frac{E_m t \sin 2\theta}{4 E_c I_c h}} \right) \tag{2}$$

3. DEVELOPMENT OF FRAGILITY CURVES

3. 1. Fragility Curve Generation using the IDA
IDA is the non-linear dynamic analysis, which is carried out by considering different Scaled earthquake ground motions for different peak ground accelerations (PGA) up to the failure of structure. This method involves scaling of each ground motion into a set until it causes collapse of structure [16]. In this approach, a suite of code-based spectrum compatible ground motions scaled to various PGAs have been considered. Several seismic codes recommend a minimum of three or seven sets of ground motions to provide a more accurate estimate of the engineering demand parameters (EDPs), (ATC 1996, UBC 1997, IBC 2000, FEMA-356, EC8, NEHRP 2005, and ASCE 2006). Further, most of the available literature, have either used an ensemble of three sets of accelerograms or seven sets of accelerograms for performance assessment using IDA [12, 22, 25-27]. Therefore, a set of seven ground motions records with respective Record Sequence Numbers (RSN) as per PEER database are chosen as shown in Table 2, satisfying the following criteria: (i) shear wave velocity ($V_{s,30}$) in the range of 200-400m/s and (ii) Earthquake magnitude ranging from 6 to 8. These ground motions were made compatible with the response spectrum from IS 1893 (Part 1): 2016 [8]. An ensemble of accelerograms is chosen to include the intrinsic uncertainties associated with the seismic ground motions (i.e., amplitude, frequency and significant duration). The obtained time-history data were incrementally scaled with respect to peak ground acceleration from 0.05 g to 1 g at an increment of 0.05 g. For each scaled time-history data, non-linear direct-integration time-history analysis was carried out to evaluate the displacement response of the frames for the corresponding input ground motion. Inter-story drift ratios of the structural models are calculated as intensity measure (IM), and IDA curves are developed. IDA curves plotted between PGA and maximum inter-story drift ratios (IM) as shown in Figures 3 and 4. Considering the IDA curves generated, the fragility parameters (i.e., the mean 'μ' and standard deviation 'σ' values) are computed as per ATC 40 [12] for different damage states are shown in Table 3, which are further used to compute the probability of exceedance as per the equation is given below:

$$P\left[\frac{D}{PGA}\right] = \phi\left[\frac{\ln(PGA) - \mu}{\sigma}\right] \tag{3}$$

Fragility curves depicted as a plot of the probability of exceedance of damage (PGA) for a given damage measure (Inter-story drift ratio is developed using spreadsheet from the seismic response given by SAP2000 is shown from Figures 5 and 6.

TABLE 2. Selected Earthquake Records from PEER database (From https://ngawest2.berkeley.edu/)

S. No.	Earthquake	RSN	Magnitude	$V_{s,30}$ (m/s)
1	Imperial Valley-02, 1940	6	6.95	213.44
2	Kern County, 1952	15	7.36	385.43
3	Northern Calif-03, 1954	20	6.5	219.31
4	Parkfield, 1966	30	6.19	289.56
5	San Fernando, 1971	68	6.61	316.46
6	Managua Nicaragua-01, 1972	95	6.24	288.77
7	Imperial Valley-06, 1979	158	6.53	259.86

(a)

(b)

Figure 3. IDA curve of G+5 (a) bare (b) OGS frame

(a)   (b)

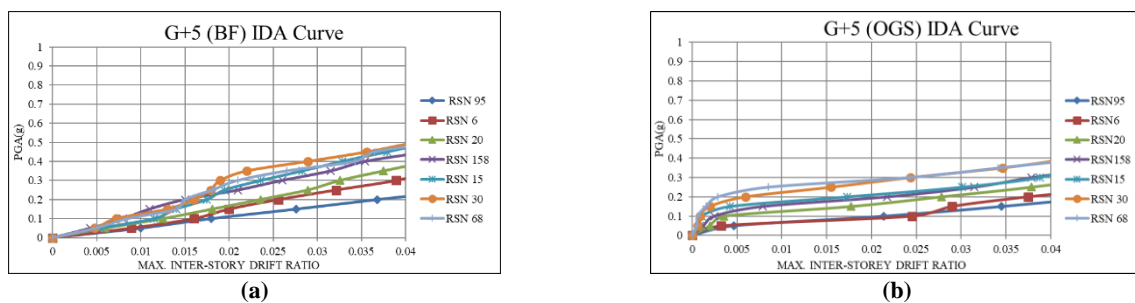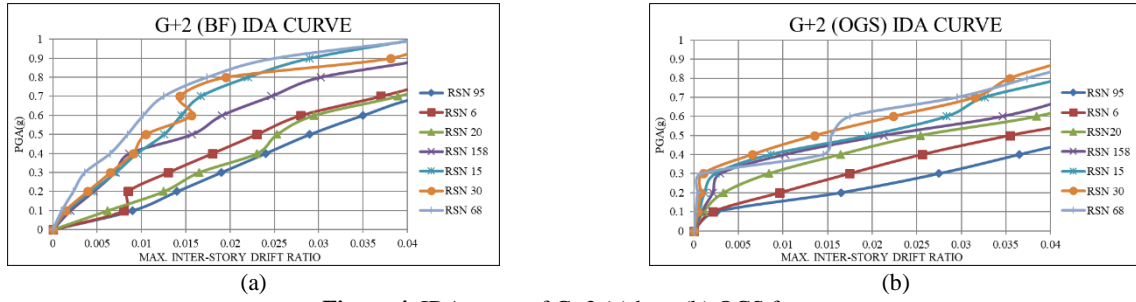**Figure 4.** IDA curve of G+2 (a) bare (b) OGS frame

(a)   (b)

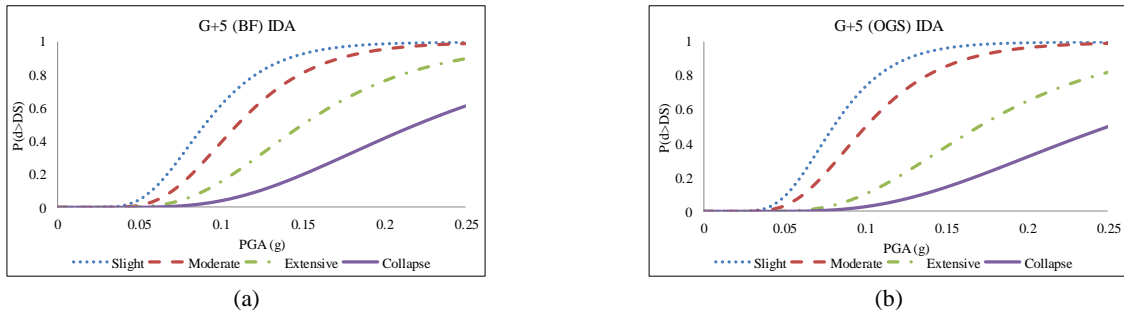**Figure 5.** Fragility curve of G+5 (a) bare (b) OGS frame

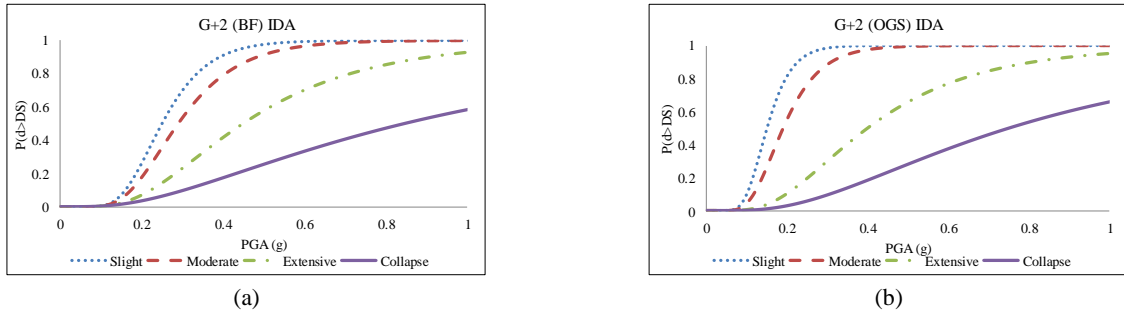(a)   (b)

Figure 6. Fragility curve of G+2 (a) bare (b) OGS frame

3. 2. Fragility Curve Generation using the CSM
Fragility curves were developed using the CSM approach specified in ATC 40 [15]. The capacity of the structure and its performance for various damage states were assessed by performing a non-linear static analysis on the structural model. The outcome of non-linear static analysis is a capacity curve, a plot between base shear and roof displacement. Further, the yield spectral displacement and ultimate spectral displacement were obtained from the bi-linearization of capacity curves in Acceleration Displacement Response Spectrum (ADRS) format [4]. The fragility parameters, spectral displacement ($S_{d,dsi}$) and standard deviation (β_{dsi}) estimated from the bilinear capacity curve are shown in Table 3. Fragility curve for a given damage state dsi is defined by lognormal probability density function given below and the developed fragility curves are shown in Figures 7 and 8.

$$P\left[\frac{ds_i}{S_d}\right] = \phi\left[\frac{1}{\beta_{ds_i}}\ln\left(\frac{S_d}{\overline{S}_{d,ds_i}}\right)\right] \tag{4}$$

4. RESULTS AND DISCUSSION

4. 1. Influence of Infill Wall on the Seismic Behavior   Comparing the fragility curves developed for BF and OGS structural models using both CSM and IDA approaches, significant variations in damage probability of OGS can be observed of the order of more than 10% compared to BF model for extensive and collapse limit states. This signifies the sensitivity of interaction of the infill wall with the bare frame during seismic excitations. Hence, the interaction of infill wall needs to be considered in vulnerability assessment of RC building structures.

TABLE 3. Mean and Standard deviation parameters for developing fragility curves

| Frame	No. of Story	IDA								CSM							
		Damage States								Damage States							
		Slight		Moderate		Extensive		Collapse		Slight		Moderate		Extensive		Collapse	
		μ	σ	μ	σ	μ	σ	μ	σ	$\bar{S}_d$	β	$\bar{S}_d$	β	$\bar{S}_d$	β	$\bar{S}_d$	β
BF	3	0.25	0.35	0.29	0.423	0.45	0.57	0.812	0.803	8.68	0.75	12.4	0.92	31.225	1.01	87.7	1.1
	6	0.09	0.35	0.11	0.37	0.15	0.4	0.22	0.45	15.89	0.68	22.7	0.72	36	0.77	76.2	0.87
OGS	3	0.15	0.32	0.19	0.38	0.4	0.55	0.74	0.7	3.647	0.75	5.21	0.92	23.83	1.01	79.7	1.1
	6	0.08	0.35	0.1	0.38	0.17	0.42	0.25	0.48	4.606	0.68	6.58	0.72	17.56	0.77	50.5	0.87

(a) (b)
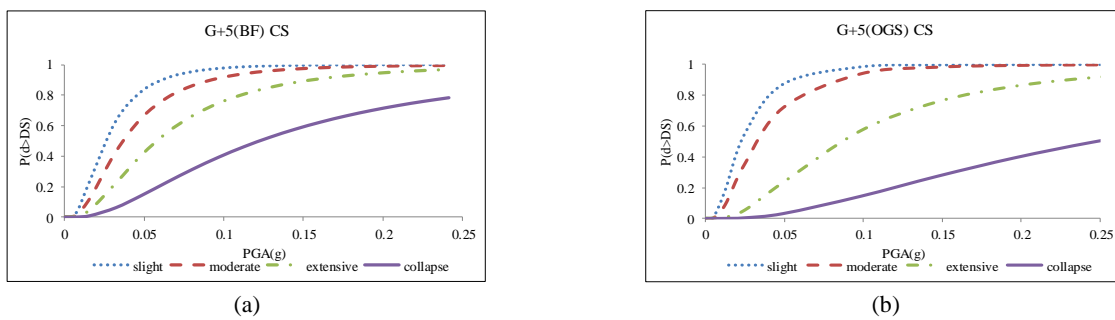
Figure 7. Fragility curve of G+5 (a) bare (b) OGS frame
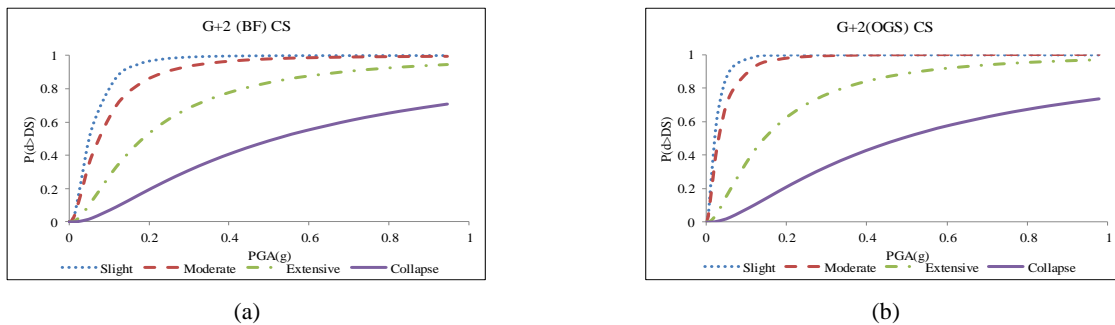

(a) (b)

Figure 8. Fragility curve of G+2 (a) bare (b) OGS frame

4. 2. Influence of Real Ground Motion Data
Fragility curves are generated considering the response spectrum specified by IS 1893 (Part 1): 2016 for type 1 soil profile using CSM. Fragility curves were also developed using a suite of accelerograms specified in Table 2 with IDA. Further, Fragility curves generated by both approaches are compared to understand the sensitivity of real ground motion records in characterizing the performance of Indian code designed RC buildings. These are described as damage probability matrices for particular damage state (Slight, Moderate, Extensive, and Collapse as S, M, E, and C). The probability of exceedance for different damage states with respect to PGA values obtained using both the approaches is shown in Tables 4-5. The structural model

is considered to be located in seismic zone III which can have likelihood of occurrence of PGA values of around 0.16g during the lifetime of a structure. Hence, the PGA values of 0.1g and 0.2g are chosen in this investigation. Further, to understand the sensitivity of ground motion data, the discrete damage probability matrices were developed for different damage states considering PGA (g) of 0.1g and 0.2g, which are derived from fragility curves represented in Figures 5 to 8.

The following can be observed from damage probability matrices shown in Tables 4 and 5 for different damage states, developed using CSM and IDA approaches:

• The CSM approach appears conservative in predicting the damage pertaining to Slight and

TABLE 4. Damage Probability Matrices of Mid-Rise frames

PGA(g)	Frame	Probability of exceedance											
		IDA				CSM				% difference between IDA & CSM			
		S	M	E	C	S	M	E	C	S	M	E	C
0.1	Bare	0.618	0.398	0.095	0	0.976	0.913	0.543	0.03	35.8	51.5	44.8	3
	OGS	0.738	0.5	0.103	0	0.984	0.938	0.567	0.1	24.6	43.8	46.4	10
0.2	Bare	0.987	0.923	0.612	0.114	0.989	0.986	0.793	0.273	0.2	6.3	18.1	15.9
	OGS	0.995	0.965	0.654	0.154	0.999	0.993	0.837	0.394	0.4	2.8	18.3	24

TABLE 5. Damage Probability Matrices of Low-Rise frames

PGA(g)	Frame	Probability of exceedance											
		IDA				CSM				% difference between IDA & CSM			
		S	M	E	C	S	M	E	C	S	M	E	C
0.1	Bare	0.563	0.312	0.03	0	0.979	0.923	0.478	0.01	41.6	61.1	44.8	1
	OGS	0.815	0.553	0.105	0	0.997	0.971	0.593	0.08	18.2	41.8	48.8	8
0.2	Bare	0.812	0.628	0.156	0	0.992	0.984	0.673	0.254	18	35.6	51.7	25.4
	OGS	0.984	0.885	0.304	0.02	0.999	0.993	0.768	0.335	1.5	10.8	46.4	31.5

Moderate damage states, whereas the variations were found to be of the order of around 20% when computed using IDA approach.

- This study necessitates the importance of real ground motion data in characterizing the damages of RC structures. Since most of the Indian code designed RC structures have been reported to suffer damages in slight and moderate limit states during past earthquake studies, it is beneficial to consider the real earthquake data suitable to the characteristics of the proposed location for analysis and subsequent design.
- The average variation between the probabilities of exceedance for S, M, E, and C damage states determined using the CSM and the IDA are 17%, 31%, 40%, and 14%, respectively.
- The effect of infill wall in OGS frames is also evident from the results, which is higher in the case of low-rise frames (5-25%) than that in case of mid-rise frames (5-10%).
- From Table 3, it can be noted that in the CSM approach, the standard deviation parameter is higher than that of IDA leading to increase in probability of exceedance of damage in CSM compared to IDA.
- The probabilities of exceedance computed for different damage states using CSM are significantly higher (of the order of 15-30%) compared to those computed using IDA. This signifies the conservativeness pronounced by CSM in predicting the damages, thereby leads to uneconomical design.

- The sensitivity of interaction of infill wall with the bare frame can be noted in terms of variations in probabilities of exceedance for various limit states. This behavior is in line with the observations made on the behavior of the infill wall in the literature during past earthquakes.

5. CONCLUSION

The present investigation focused on understanding the impact of utilizing the real ground motion records on the performance assessment of RC buildings with and without consideration of infill walls. Fragility curves were developed for the structural models using Capacity Spectrum Method (CSM) specified by ATC-40 and with Incremental Dynamic Analysis (IDA). It can be observed that the average variation between the probabilities of exceedance for S, M, E, and C damage states determined using the CSM and the IDA are 17%, 31%, 40%, and 14%, respectively. This clearly pronounces the necessity of using real ground motion data wherever possible. The sensitivity of interaction of infill wall with the bare frame can be noted in terms of variations in probabilities of exceedance for various limit states as discussed. This emphasizes accounting of infill wall interaction in vulnerability assessment of structures. These are in line with the observations reported in literature during past earthquakes. Hence, it is recommended to utilize the real earthquake data wherever possible for more accurate

seismic analysis and performance characterization of structures thereby leading to economical design.

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چکیده

ساختمانهای بتونی با آرماتور با طبقات زمین باز (OGS) یکی از رایج ترین پیکربندی های ساختمان در زیستگاه شهری شناخته شده است. که این ساختمان ها در برابر تحریکات لرزه ای آسیب پذیر می باشد ، در درجه اول به دلیل از دست دادن ناگهانی قدرت در طبقه همکف و توزیع سختی دیفرانسیل در کل ساختار. توزیع سختی دیفرانسیل در درجه اول به تعامل غیر ساختاری با قاب مقاومت لحظه ای نسبت داده می شود. از این رو ، برآورد آسیب پذیری لرزه ای ، باید برهم کنش دیواره نافذ حساب شود. بنابراین ، پژوهش حاضر با درک تأثیر استفاده از سوابق حرکت زمین واقعی در ارزیابی عملکرد ساختمانهای RC با و بدون در نظر گرفتن دیوارهای فرو ریخته متمرکز شده است. منحنی های شکنندگی برای مدل های ساختاری کم و متوسط با استفاده از روش طیف ظرفیت (CSM) مشخص شده توسط ATC-40 و با تجزیه و تحلیل دینامیکی افزایشی (IDA) توسعه یافته توسعه داده شد. از طیف پاسخی مشخص شده توسط کد مربوطه ، برخلاف IDA که در آن مجموعه ای از شتاب دهنده های حرکت زمین واقعی سازگار با طیفی که شرایط سایت راضی سازند ، در ارزیابی عملکرد استفاده گردید. علاوه بر این ، تغییرات قابل توجهی مشاهده شده در منحنی های شکنندگی توسعه یافته توسط CSM & IDA بر حساسیت داده های حرکت زمین واقعی در ارزیابی عملکرد تأکید دارد.

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