

Collapse Assessment of Substandard Concrete Structures for Seismic Loss Estimation of the Building Inventory in the UAE

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Abstract Regional earthquake loss estimation systems describe the probability of losses that could happen by a seismic hazard to a certain region. In order to develop a loss estimation system for a region, the vulnerability characteristics of the exposed structures should be integrated with earthquake hazard and the inventory of the built environment. The accurate definition of structural collapse under earthquake loads is essential for deriving reliable vulnerability functions. In this study, the collapse of concrete buildings is described in terms of both global structural response and member failure, including shear failure modes. Experimentally verified shear strength models that effectively consider the reduction of shear strength with the concrete degradation under cyclic loading are implemented in a post-processor to monitor the shear supply-demand response of concrete structures under earthquake loads. A wide range of reference structures with diverse lateral force resisting systems and building heights is selected to represent substandard buildings in the UAE. Detailed fiber-based numerical models and a diverse set of earthquake records representing different seismic scenarios in the study region are employed in dynamic response simulations at various levels of ground motion intensities up to collapse. The effectiveness of the adopted shear strength models in predicting the brittle failure modes of substandard concrete buildings is demonstrated in this study. It is concluded that shear modeling is essential for the reliable earthquake loss estimation of pre-seismic code buildings. The advanced vulnerability functions confirm the need for mitigation strategies to reduce the earthquake losses of the

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substandard building inventory in the study area. This comprehensive study represents a step forward for the development of a reliable loss estimation system in the UAE and the surrounding region.

Keywords Earthquake loss estimation • Vulnerability assessment • Substandard buildings • Shear failure • Inelastic dynamic simulations • UAE

1 Introduction

The pre-seismic code reinforced concrete (RC) structures represented in the building inventory of the UAE need a focused attention. Although the UAE is considered a low-to-medium seismicity region as per recent seismic hazard studies, old buildings designed to resist gravity, and wind loads only may be vulnerable to earthquake losses due to the lack of adequate seismic provisions at the construction time (Mwafy et al. 2006). This is particularly true in the light of the continuous updates in seismic hazard maps for the region. A systematic seismic vulnerability assessment is highly needed to predict the performance of such structures under the effect of the earthquake scenarios anticipated in the studied area (i.e., UAE). The realistic definitions of performance criteria and brittle failure modes are essential for assessing the vulnerability of substandard buildings.

Shear failure of RC structures implies rapid strength degradation and loss of energy dissipation capacity (Mwafy and Elnashai 2008). Therefore, monitoring the shear response of RC structures, particularly substandard buildings, could be inevitable for the accurate assessment of their seismic losses. This reflects the pressing need for efficient approaches that enable tracing brittle shear failure modes in RC structures using experimentally verified shear strength models. This study thus focuses on the vulnerability assessment of sample buildings that represent substandard RC structures in the UAE, taking into consideration the reliable assessment of shear response under the effect of different earthquake scenarios anticipated in the study region. The shear prediction models that have proven experimentally to account for the impacts of shear-axial interaction and ductility on shear strength are considered with an emphasis on substandard RC buildings.

2 Reference Structures and Ground Motions

2.1 Selection, Design, and Modeling of Pre-seismic Code Structures

This study focuses on the vulnerability assessment of the pre-seismic code building inventory in a highly populated and active seismic area in the UAE (i.e., Dubai, Sharjah, and Ajman). The reference buildings of the present study are selected

based on a building database collected for the study area (Mwafy 2012; Mwafy et al. 2015). On-ground surveys and site visits were conducted to collect the building database with the help of high-resolution satellite images. The collected structures were categorized according to four criteria, namely the building height, function, construction date, and population intensity. The buildings constructed before 1991 are considered as pre-code structures since a large percentage of these structures were designed to resist gravity and wind loads only. According to the inventory mentioned above, five RC buildings of 2, 8, 18, 26, and 40 stories were selected and designed (Issa and Mwafy 2014). Table 1 summarizes the general details of the selected reference buildings while Fig. 1 depicts the buildings classification in the study area according to their construction date. The selected 2- and 8-story buildings are frame buildings, while the 18-, 26- and 40-story buildings are shear wall structures. The analysis and design of the reference buildings were carried out using the British Standards and the ETABS structural analysis software (BS8110 1986; CSI 2011). The material properties were selected to represent those expected at the time of construction (Issa and Mwafy 2014). The required amount of longitudinal reinforcement was calculated for the columns, walls and core walls of the reference buildings. The design shear strength is estimated and compared with the shear demand to calculate the transverse reinforcement.

Detailed modeling of the reference structures was conducted for inelastic analysis (Issa and Mwafy 2014). The numerical models were developed using the inelastic analysis platform ZEUS-NL (Elnashai et al. 2012). The materials were selected to idealize effectively the reinforcing steel bars, confined, and unconfined concrete during the inelastic simulations. For the 40-, 26- and 18-story structures, the reference buildings were idealized as two-dimensional (2D) systems. The frame structures (i.e., 2- and 8-story buildings) were idealized as three-dimensional (3D) models. The finite element models (design) and fiber-based (assessment) models of all reference buildings are depicted in Fig. 2.

Table 1 Details of the reference buildings (Issa and Mwafy 2014)

Number	Building reference	No. of stories	Story height (m)			Total height (m)
			B	GF	TF	
1	BO-02	2	–	5.0	3.5	8.5
2	BO-08	8	–	5.0	3.5	28.5
3	BO-18	18	3.2	4.5	3.2	58.9
4	BO-26	26	3.2	4.5	3.2	84.5
5	BO-40	40	3.2	4.5	3.2	129.3

B basement; *GF* ground floor; *TF* typical floor

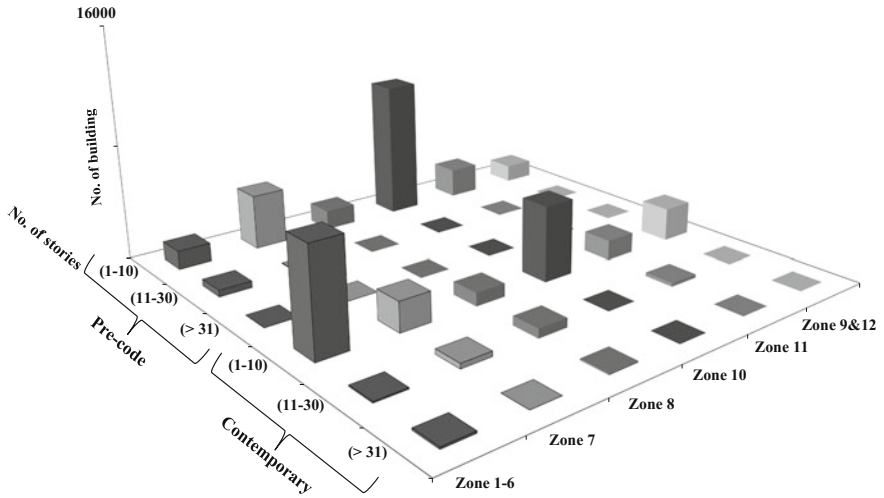


Fig. 1 Buildings classification according to their construction date (Issa and Mwafy 2014)

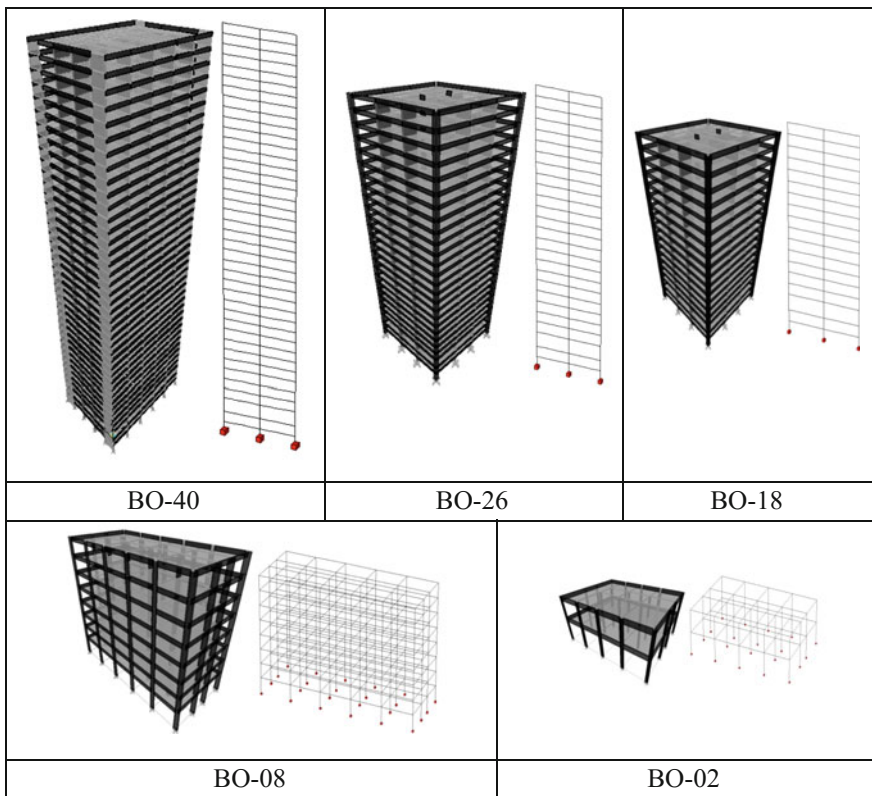


Fig. 2 Finite element and fiber-based models of reference structures

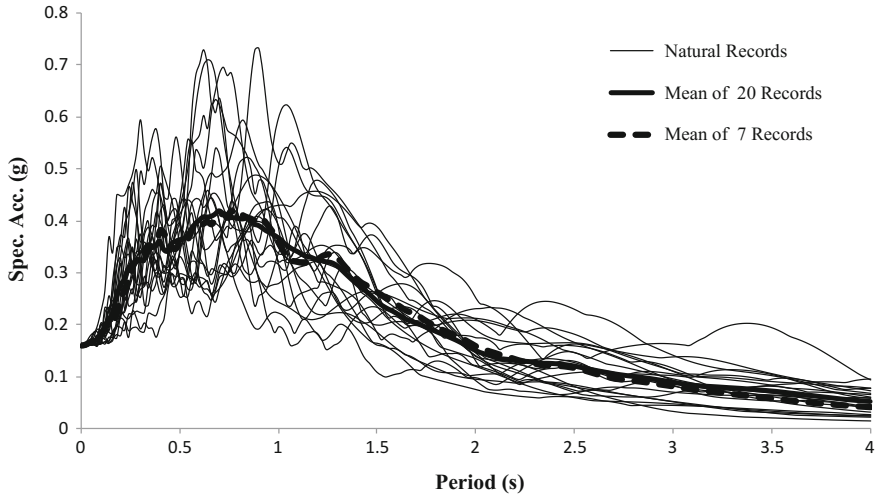
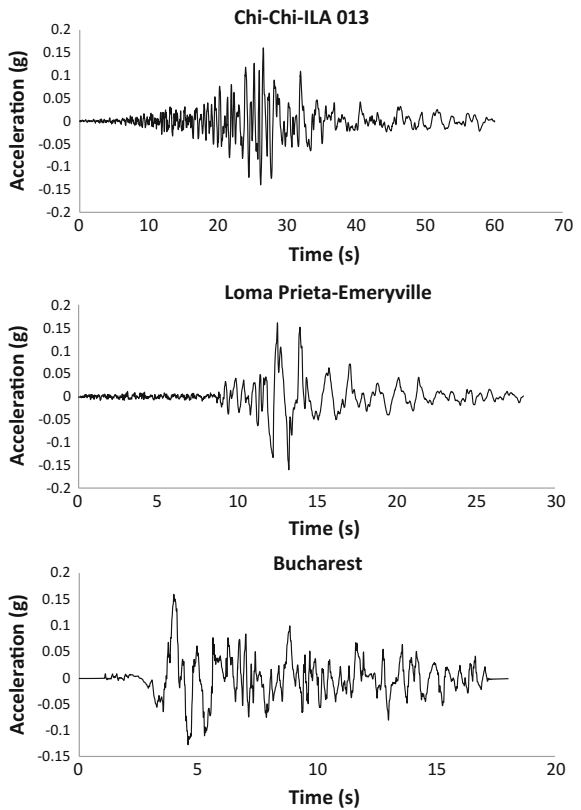


Fig. 3 Comparison of mean response spectra of two groups of 20 records and seven events representing far-field earthquake scenarios

Fig. 4 Sample of the selected far-field earthquake records



2.2 Selection of Scenario-Based Earthquake Records

Two earthquake scenarios representing far-field and near-source earthquake records are adopted in this study based on the recommendations of previous seismic hazard studies for the UAE (Mwafy et al. 2006). Fourteen far-field and near-source records are selected to represent the two seismic scenarios mentioned above. The mean of the selected records matches the mean of 40 earthquake records used in previous vulnerability assessment studies for the UAE (Mwafy 2012; Mwafy et al. 2015). The response spectra of 20 far-field earthquake records along with their mean are compared with the mean of selected seven records in Fig. 3. Samples of the selected far-field earthquake records are also shown in Fig. 4.

3 Performance Assessment of Existing Structures

3.1 Shear Demand-Supply Response at the Member Level

A literature review is carried out to select experimentally verified shear strength models in addition to the code design approach for the assessment of the shear response of RC columns and shear walls. Five shear strength models for RC columns are selected, namely those proposed by Kowalsky and Priestley 2000; Priestley et al. 1994; Sezen and Moehle 2004; Kim et al. 2012; Howser et al. 2010; Bentz et al. 2006. The latter shear strength approach is based on the simplified modified compression field theory (SMCFT). Three shear strength models for walls are selected, namely those recommended by Kowalsky and Priestley 2000; Priestley et al. 1994; Wallace 2010; Krollicki et al. 2011. The design provisions currently implemented in the reference study area is also used in the shear performance assessment (ACI-318 2011). The performance assessment of the reference structures is conducted using both the inelastic pushover analysis (IPA) and time history analysis (THA). The response of each of the investigated buildings is presented at three critical story levels, namely at the basement level, building mid-height and the roof of each structure. The shear response is traced, and any indications of shear failure in structural members are reported when the shear demand exceeds the capacity.

The structural performance is verified using IPA by applying lateral load along the building height (Mwafy and Elnashai 2001). The shear supply is compared with the shear demand of structural member at different inter-story drift ratios (IDRs). Sample results for the shear response of the 18-story building are presented in Fig. 5. Shear failure is observed in the core walls and external shear walls at the basement level as per the Wallace (2010) shear strength model. The axial force increases with increasing lateral loads, and the shear demand exceeds the supply

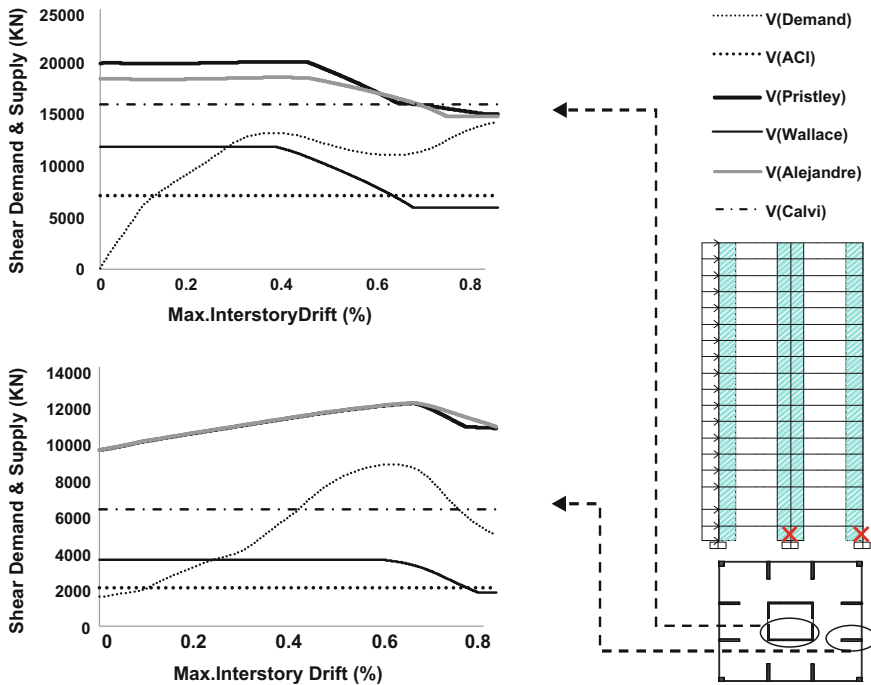


Fig. 5 Shear demand-supply response of core walls and external shear walls at the basement level using IPA (18-story building)

causing shear failure. The negative impact of ductility demands on the shear supply under high levels of lateral loads and IDRs is shown from the shear response predicted using the Priestley (Kowalsky and Priestley 2000), Calvi (Krolicki et al. 2011) and Wallace (2010) shear strength models.

Furthermore, the shear response of the reference structures is monitored under the effect of two earthquake scenarios at different intensity levels. Sample results are presented in Fig. 6 for the 40-story building under the near-source earthquake record Lazio Abr. It is shown that the core walls at the basement level fail in shear at high PGA levels. All of the selected shear strength models detect shear failure. Under near-source earthquake records, the shear response is significantly influenced by the variation of axial loads, without observable effects from ductility.

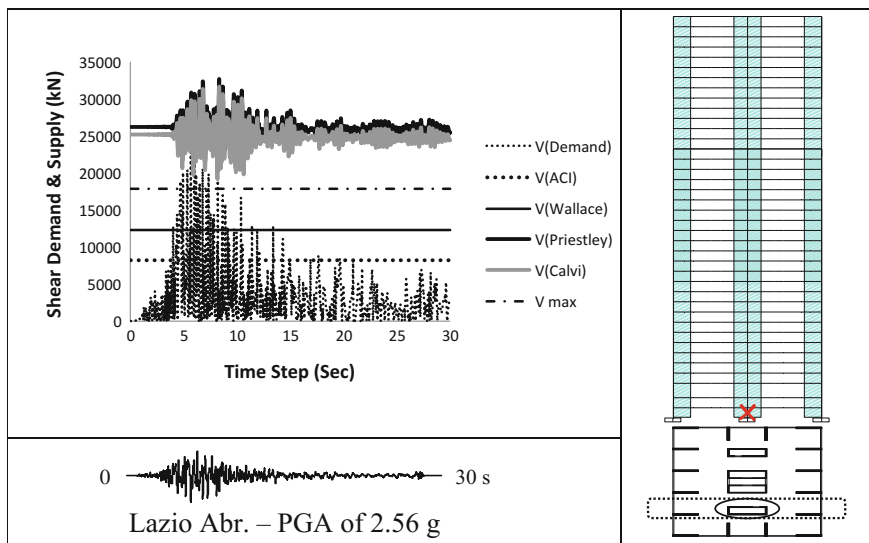


Fig. 6 Shear demand-supply response of the core walls of the 40-story building at the basement level under a near-field earthquake record

4 Selection of Performance Indicators

Three performance limit state criteria are adopted for fragility analysis, namely immediate occupancy (IO), life safety (LS), and collapse prevention (CP). The IO limit state defines a minor damage state in which the building remains safe to occupy after the earthquake while any needed repairs are minor. The LS limit state represents a significant damage sustained by the building while the structure still has some reserve capacity. The CP limit state defines a significant state of damage in which the building is on the verge of structural collapse (Jeong et al. 2012). THAs are carried out to predict the shear failure of the reference buildings, and IDRs are obtained once the shear failure is detected from different seismic scenarios. The average IDRs when shear failure is detected in the five reference buildings are presented in Fig. 7 for the far-field earthquake records. The comprehensive results obtained from a large number of far-field and near-source earthquake records indicate that the average IDR values at shear failure obtained from the near-source records are less than those from far-field events for the shear wall structures. On the other hand, the average IDRs of the frame structures at shear failure increase under the effect of near-source records when compared with the far-field counterparts. The results suggest adopting seismic scenario-based limit state criteria to quantify the level of damage to different structural systems.

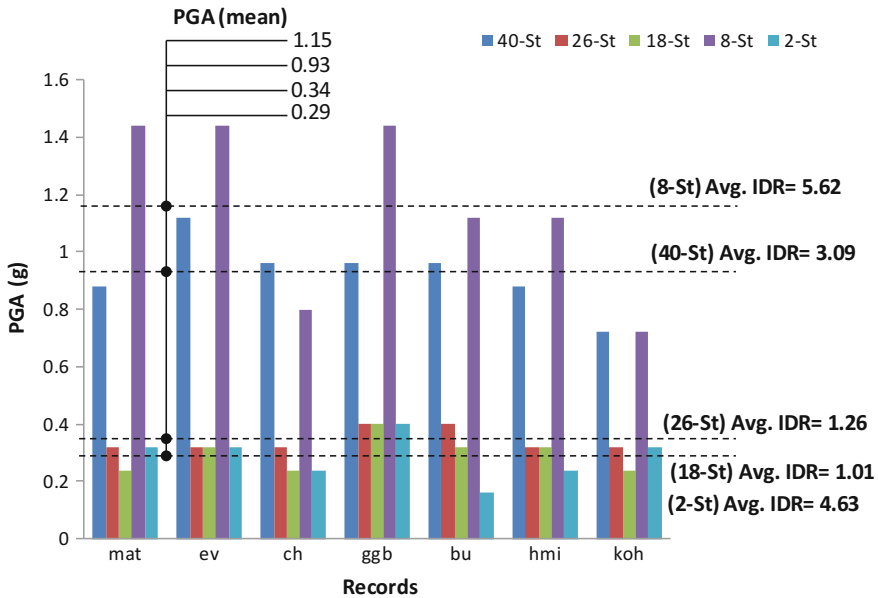


Fig. 7 Average IDRs of five reference buildings under the effect of seven far-field earthquake records

The performance criteria of the reference structures were selected in a previous vulnerability assessment study without estimating the impact of shear response (Issa and Mwafy 2014; Mwafy et al. 2015). In the present study, limit state criteria are selected according to the THA results considering the effect of shear response from different earthquake scenarios on limit states. For the 40-story building, shear failures detected earlier under the near-source earthquake records compared with the far-field counterparts, as shown in Table 2. The impact of shear assessment on the results under the effect of far-field records is insignificant. For the 26- and 18-story buildings, the effects of shear response on the results obtained from both near-source and far-field earthquake records are observable, as shown in Table 2. Revised CP limit states are therefore selected for both the far-field and near-source earthquake events. On the other hand, the effect of shear assessment on the results of frame structures under both the far-field and near-source records is insignificant, and hence no changes in limit states are adopted for this class of structures. The adopted limit states in the current study are summarized in Table 2. It is noteworthy that the LS limit state is considered as 50% of the CP performance criterion (ASCE/SEI-41 2007).

Table 2 Revised limit states of five reference buildings using different earthquake scenarios considering shear assessment

Earthquake scenario	Reference structure														
	40-st			26-st			18-st			8-st			2-st		
	Limit state—inter-story drift (%)														
	IO	LS	CP ^a	IO	LS	CP ^a	IO	LS	CP ^a	IO	LS	CP ^a	IO	LS	CP ^a
Far-field records	0.34	0.89	1.78	0.34	0.63	1.26	0.34	0.505	1.01	0.39	1.48	2.96	0.39	1.48	2.96
Near-source records	0.34	0.65	1.3	0.34		0.6	0.34		0.47						

^aExcluding shear assessment, the IDR corresponding to the CP limit state was 1.78% for the 18–40 story buildings, while it was 2.96% for the 2- and 8-story structures

5 Fragility Assessment

Fragility curves represent the probability of exceeding limit states at different ground motion intensity levels (Jeong et al. 2012). The expected physical damage of a structure can be determined from fragility curves. The vulnerability functions can be therefore integrated with loss estimation systems to provide predictions of earthquake losses. Taking into consideration the revised limit states of the present study, as presented in Table 2, improved fragility curves are developed and compared with those derived in previous studies (Issa and Mwafy 2014). Since shear assessment has observable impacts on the performance of shear wall structures, revised fragility curves are only derived for this group of structures. The fragility curves of the frame structures (i.e., 2- and 8-story buildings), which were previously developed (Issa and Mwafy 2014), are unaffected by the shear assessment conducted in the present study, as shown in Fig. 8a for the 8-story building. For the 18-story building, the limit state exceedance probabilities significantly increase under the far-field earthquake records using the revised performance limit states, as presented in Fig. 8b. For the 26-story building, the limit state exceedance probabilities also increase, but with less extent, under far-field earthquake records using the revised performance limit states, as shown in Fig. 8c. The steepness of the CP and LS fragilities increases for both the 26- and 18-story buildings, while the

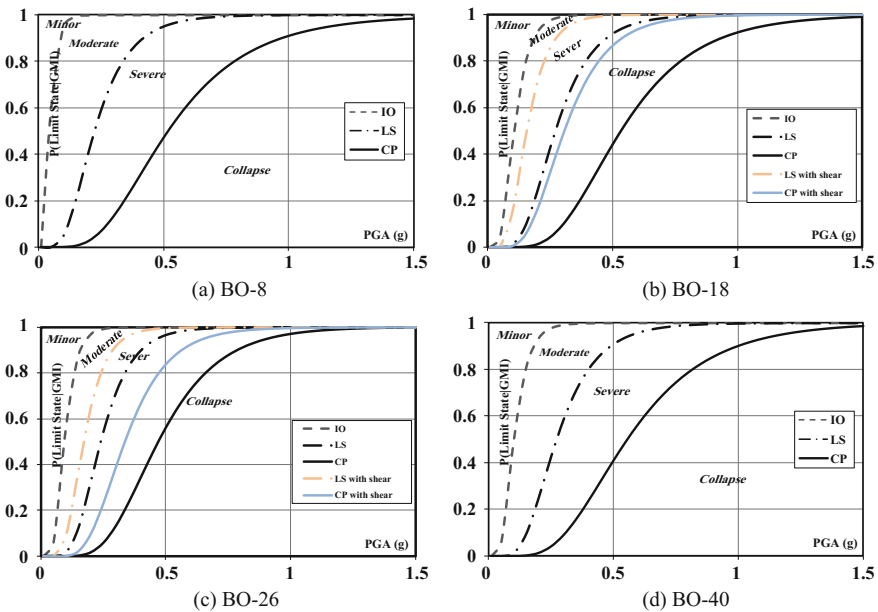


Fig. 8 Fragility curves of four reference structures using a far-field earthquake scenario

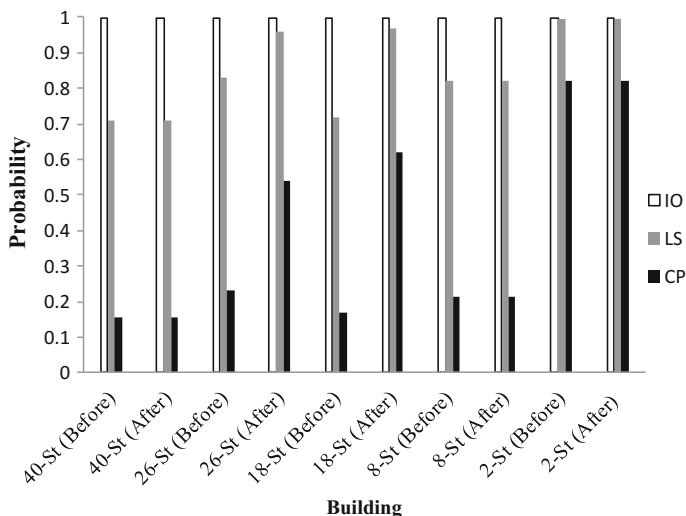


Fig. 9 Limit state exceedance probabilities for far-field earthquake records at twice the design PGA

fragility curves of the 40-story building under the far-field earthquake records remain as recommended in previous studies without any changes (Issa and Mwafy 2014; Mwafy et al. 2015), as shown in Fig. 8d.

The probability of exceeding the revised performance limit states clearly describe the impact of shear response on the probabilistic assessment study carried out for the five reference structures. Figure 9 depicts a comparison between the limit state exceedance probabilities obtained from the far-field earthquake records at twice the design PGA with and without the shear assessment of the reference buildings. The probability of damage significantly increases for the CP and LS limit states of the 26- and 18-story buildings. The results clearly suggest that the CP and LS damage probabilities increase as the height of structures decreases.

6 Conclusions

This study focused on the earthquake vulnerability assessment of frame and shear wall buildings that represent substandard RC structures in the UAE, taking into consideration the reliable assessment of failure modes. Five reference RC buildings of 2, 8, 18, 26, and 40 stories were selected, fully designed and idealized for dynamic response simulations. Two seismic scenarios representing far-field and near-source earthquake records were adopted to represent the expected earthquake scenarios in the study region. Several experimentally verified shear strength models for RC columns and shear walls were selected and implemented with other

structural performance indicators in a post-processor to enable the reliable assessment of the reference buildings under earthquake loading.

The presented sample results from inelastic pushover analyses and dynamic response simulations indicated that shear failure was detected in the pre-code shear wall structures unlike the case of frame buildings. For the 40-story shear wall building, the impact of shear assessment on the performance limit states was insignificant under the effect of far-field records, while the brittle shear failure was detected much earlier under the near-source earthquake records. For the 26- and 18-story buildings, the effects of shear response on the results obtained from both near-source and far-field earthquake records were observable, and hence revised limit states were selected for both earthquake scenarios. Seismic scenario-based performance limit states were therefore adopted based on the comprehensive results of this study to quantify the level of damage to different structural systems. Considering the proposed performance limit states, improved fragility relationships were developed for pre-code buildings. The vulnerability relationships indicated that the limit state exceedance probabilities significantly increase for the CP and LS performance criteria, particularly for medium-rise shear wall structures (i.e., 18- and 26-story buildings). The results clearly confirmed that the damage probabilities increase with decreasing the building height. This earthquake vulnerability assessment study for the pre-code buildings in the UAE contributes in developing a holistic earthquake risk management system for the building and infrastructure in the UAE and the surrounding region.

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