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IMPACT OF PREDICTING BRITTLE FAILURE MODES ON SELECTION OF LIMIT STATES OF VERTICALLY-IRREGULAR TALL BUILDINGS

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The proper definition of structural failure of irregular structures is a critical element in building vulnerability assessment. Shear force demands may be the main cause of failure under earthquake loading. This increases the uncertainty related to the definition of the limit states of irregular buildings. The present study thus focuses on the assessment of brittle shear failure on the performance criteria of vertically irregular tall buildings. Five 50-story structures are designed using international standards to represent code-conforming tall buildings with main vertical irregularities. Detailed simulation models are used to assess the failure modes of the buildings under the effect of far-field and near-source earthquake records. Experimentally verified shear strength models are adopted to monitor the shear supply-demand response of the reference structures. Based on the comprehensive results obtained from incremental dynamic analyses, it is concluded that shear modeling is essential for the reliable assessment of vertically irregular buildings. The characteristics of earthquake records and the irregularity type significantly influence the limit states of the reference buildings. Unlike the behavior of the buildings under the far-field earthquake scenario, which is controlled by flexure, the collapse prevention limit state is significantly influenced by the member shear response under the effect of near-field earthquakes. Accordingly, improved limit state criteria are proposed, which supports the reliable earthquake loss estimation of tall buildings with different vertical irregularities.

Keywords: Vertical irregularity, Shear failure, Performance criteria, Seismic response, Earthquake scenario.

1 INTRODUCTION

High-rise buildings have been rapidly increased around the world. Multiuse buildings such as parking facilities, offices, and residential and commercial buildings are widely constructed in major cities. The height range of common tall buildings is in the range of 50 - 70 stories, as per a number of surveys for the high-rise buildings around the world (e.g. Mwafy 2012). The efficient design of high-rise buildings depends on several parameters such as the structural system, construction material and analysis tool (e.g. FIB 2014). Among the lateral force resisting systems (LFRSs) of high-rise buildings, shear walls represent efficient structural system since their high stiffness and strength effectively control the lateral deformations and resist the demands imposed by earthquake and wind loads.

The abrupt changes in the stiffness, mass, geometric dimensions, and/or strength of LFRS along the building height due to architectural and services requirements introduce vertical irregularities. Hence, irregular high-rise buildings are widespread. The performance assessment at the structural member level is significant for the accurate evaluation of limit states and the seismic response of irregular high-rise structures. The main indicators for the local structural failure include the yielding of reinforcing steel and crushing of confined concrete. Additionally, the shear response of critical members should be assessed to detect any possible brittle shear failure modes (Mwafy and Elnashai 2006). Thus, the primary objective of this study is to select rational performance criteria for tall buildings depending on their irregularity category, taking into consideration the reliable representation of brittle shear failure modes.

2 DESIGN AND MODELING OF IRREGULAR BUILDINGS

Five 50-story reinforced concrete (RC) high-rise buildings are selected to represent a regular structure, extreme soft story irregularity, geometric irregularity, irregular building with in-plane discontinuity, and extreme weak story irregularity. The buildings are denoted B1-REG, B2-SST, B3-GEO, B4-DIS and B5-WST, respectively. The definitions of the selected irregularities are as per the ASCE-7 provisions (ASCE/SEI-7 2010). Figure 1 describes the selected five reference structures. Shear walls are mainly used as LFRS. The increased height of the ground story (6.5m) of B2-SST, which is more than double the typical height of the story above (3.2m), which causes a significant reduction in stiffness, and consequently the extreme soft story irregularity. Figure 1(b) shows that B3-GEO exemplifies the vertical geometric irregularity because the ratio between the LFRS length at the basement and ground stories is more than 130% (ASCE/SEI-7 2010). B4-DIS represents buildings with an in-plane discontinuity of LFRS because a transfer slab at the first story level supports the planted walls of typical stories, as shown in Figure 1(c). Finally, due to the major significant changes of the LFRS at the basement and ground stories of B5-WST, the ratio of the flexural/shear strength at the ground story to that at the first story is less than 65% of the story above, as shown in Figure 1(d). Therefore, B5-WST exhibits an extreme weak story irregularity as per the ASCE/SEI-7 (2010) definition.

The five reference structures are designed using three-dimensional (3D) models (ACI-318 2011). The concrete strength, $f_c^`$, varies throughout the height of vertical element, starting from 48 MPa at the foundation to 32 MPa at the roof. The concrete strength of all slabs and beams is 32 MPa, while the yield strength, f_y, of reinforcing steel bars is 460 MPa for flexural design and 420 MPa for shear design (ACI-318 2011). Permanent loads include the self-weight of structural members with superimposed dead load of 4.0 kN/m2. Live loads are 2.0, 4.8 and 3.0 kN/m2 for the residential areas, corridors and staircases, and basements, respectively. The case study area (Dubai, UAE) represents a region of medium seismicity. The seismic design category is ‘C’, while the site class is very dense soil (ASCE/SEI-7 2010).

Simulation models are developed in this study to represent the LFRSs of the five reference buildings in the transverse direction using Zeus-NL (Elnashai *et al.* 2012). It is noteworthy that certain irregularities are introduced in the transverse direction, and hence the nonlinear analysis is conducted in this direction. Three cubic elastoplastic frame elements are used to idealize each horizontal and vertical structural member. This modeling approach adequately represents the spread of inelasticity within the cross-section and along the member length. A uniaxial constant confinement concrete model and a bilinear elastoplastic steel model with kinematic strain-hardening are used in the Zeus-NL models (Elnashai *et al.* 2012). It is important to note that the Zeus-NL modeling approach and key modeling parameters adopted in the present study has been recently verified by comparisons with the nonlinear dynamic response of a full-scale seven-story wall building (Alwaeli *et al.* 2016).

As per the recommendation of previous studies for the case study area, a seismic scenario-based assessment is performed in the present study (e.g. Mwafy *et al.* 2006). The employed seismic scenarios represent: (i) severe earthquakes with a long epicentral distance, and (ii) moderate events with a short distance from the epicenter. The earthquake record magnitude, epicentral distance, soil class and PGA are thus considered for the selection of 20 far-field and 20 near-field natural records to represent the seismic scenarios expected in the case study region (PEER 2015). The selected earthquake records are initially scaled to a PGA of 0.16g, which represents the design PGA for 10% probability of exceedance in 50 years.

Figure 1. Selected reference structures: (a) typical layout; (b) B3-GEO configuration and layout, (c) B4-DIS layout at the irregularity level, and (d) B5-WST layout at the irregularity level.

3 ASSESSMENT OF SHEAR DEMAND-SUPPLY RESPONSE

The yielding of reinforcing steel, crushing of confined concrete and shear failure modes of the five reference structures are assessed in detail. For the sake of brevity, only the shear demands of critical structural members are compared with the shear strength to provide insights into the shear failure potential. The results related to yielding of steel and crushing of concrete are discussed by Mwafy and Khalifa (2017). The experimentally verified shear strength model proposed by Priestley *et al.* (1994) is adopted in the current study to estimate the shear capacity. Incremental dynamic analyses (IDAs) are used for shear response assessment. Sample results are shown in Figures 2 and 3, which depict comparisons between the shear demand, Vde, shear strength using the ACI-318 (2011) approach, V(ACI), and shear supply using the Priestley *et al.* (1994) model, Vpr. It is shown in Figure 2, which illustrates the shear force assessment results using a long-period earthquake record (Chi-Chi, TAP021, 1999) of sample buildings, that shear failure is not detected in the reference buildings before reaching the preliminary collapse prevention (CP) limit state. This is attributed to the impact of long-period records on high-rise buildings in which the flexural response is more significant than shear. On the other hand, Figure 3 shows that the short-period earthquake records have a considerable impact on the shear response and the limit states of irregular structures. For the short-period earthquake scenario, which is represented by Friuli (Breginj-Fabrika IGLI, 1976) the interstory drift ratio (IDR) corresponding to shear failure significantly decreases as a result of the detected shear failure before the preliminary CP limit state. It is important to note that the shear failure is detected when Vpe-Vpr exceeds zero.

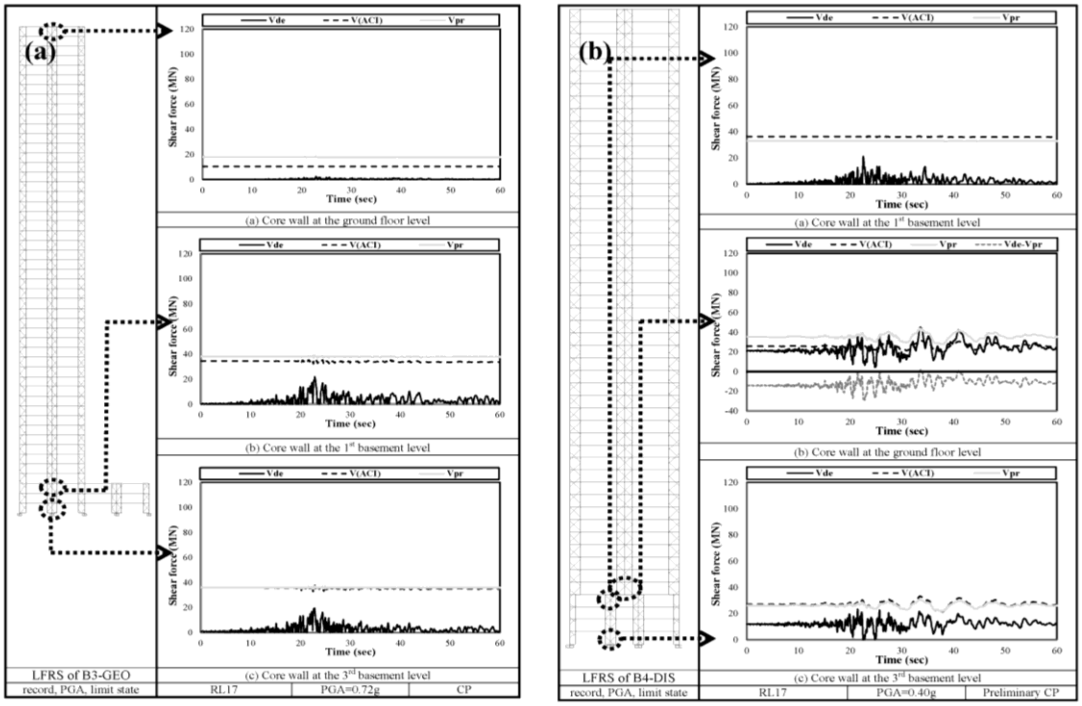

Figure 2. Shear demand using a long-period record versus shear strength using ACI and Priestley *et al.* (1994) models for the core walls: (a) B4-GEO, and (b) B4-DIS.

4 IMPROVED PERFORMANCE LIMIT STATES OF IRREGULAR BUILDINGS

The performance criteria adopted in the current study include: (i) immediate occupancy, IO, (ii) life safety, LS, and (iii) collapse prevention, CP. The local and global response of the reference structures and the experimental results of previous studies are used to identify IDR corresponding to different limit states (Mwafy and Khalifa 2017). The preliminary limit states are re-evaluated based on the shear response assessment. The CP limit states of the benchmark buildings are not influenced by the effect of long-period earthquake records, as shown in Figure 2 and Table 1. In contrast, the shear response assessment results using the short-period records have a significant effect on the CP limit states of the five reference buildings (Figure 3 and Table 1). From Table 2 it is decided to select two groups of limit states depending on the earthquake scenario.

5 CONCLUSIONS

The impact of brittle shear failure modes on the limit states of regular and vertically irregular high-rise structures were assessed in this study. Five 50-story buildings were designed and modeled using a fiber-based modeling approach to evaluate their vulnerability to shear failure using IDAs and earthquake records representing two earthquake scenarios. It was concluded that the limit states of the reference buildings were significantly influenced by the characteristics of the earthquake records and the irregularity type. For the far-field earthquake scenario, the limit states were controlled by flexure. The IDRs corresponding to the CP limit state of the B1-REG, B2-SST, B3-GEO, B4-DIS and B5-WST buildings were 2.27%, 2.26%, 2.39%, 1.18% and 1.38%, respectively. For the near-field earthquake scenario, the CP limit state was significantly influenced by the member shear response. Accordingly, the IDRs corresponding to the CP limit state of the five buildings were 1.55%, 1.5%, 1.62%, 0.64% and 0.78%, respectively. The improved limit state criteria proposed in this study help to arrive at reliable fragility relationships and earthquake loss estimation of tall buildings with different vertical irregularities.

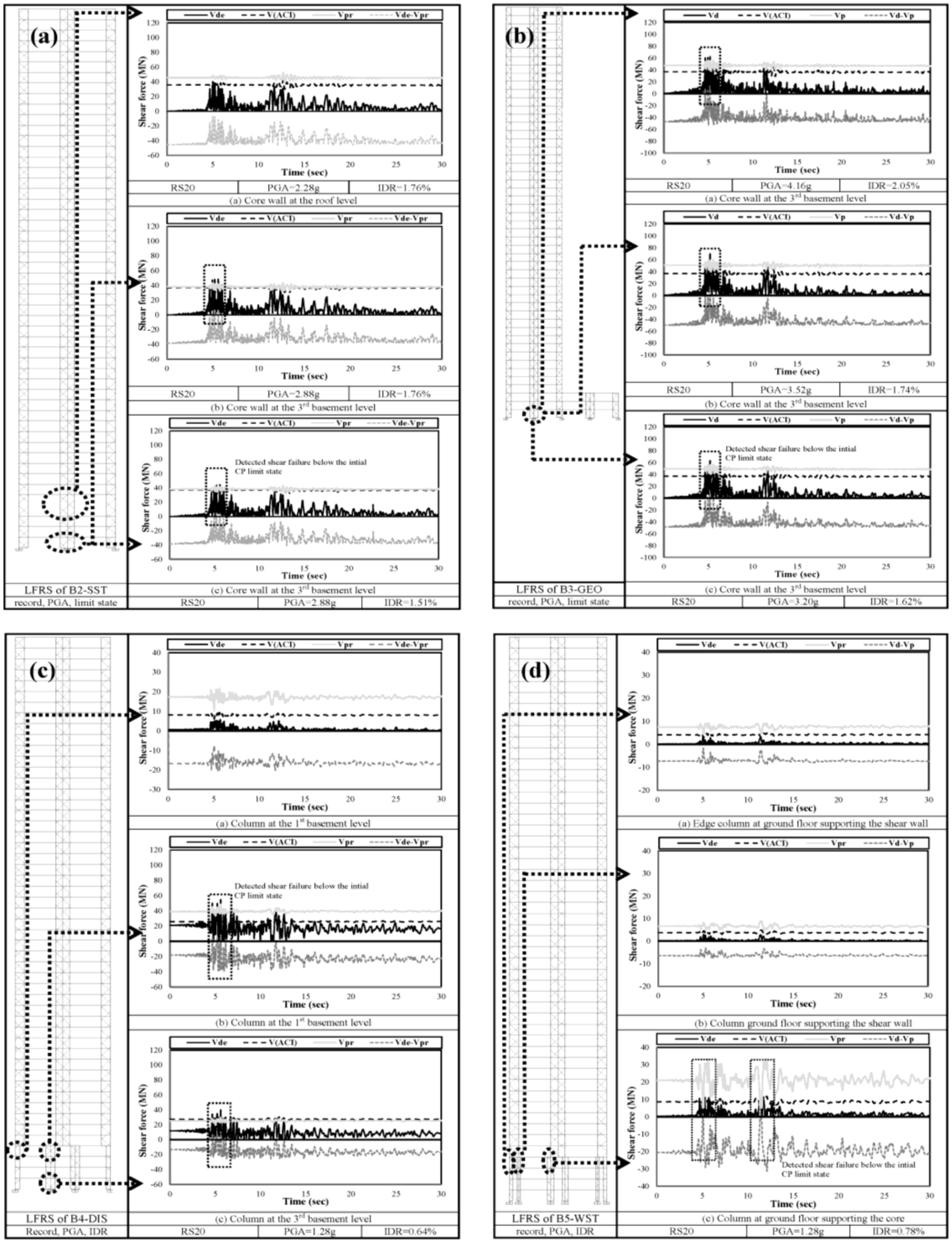

Figure 3. Shear demand using a short period record versus shear strength using ACI and Priestley *et al.* (1994) models for critical structural members of: (a) B4-SST, (b) B4-GEO, (c) B4-DIS, and (d) B4-WST.

Table 1. Impact of shear response on limit states from different earthquake scenarios.

Record scenario	Reference structure														
	B1-REG			B2-SST			B3-GEO			B4-DIS			B5-WST		
	Limit state – interstory drift (%)														
	IO	LS	CP	IO	LS	CP	IO	LS	CP	IO	LS	CP	IO	LS	CP
Long period records	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Short period records	-	-	1.55	-	-	1.50	-	-	1.62	-	-	0.64	-	-	0.78

[-] Not affected

Table 2. Improved earthquake scenarios-based limit states of reference buildings considering shear.

Record scenario	Reference structure														
	B1-REG			B2-SST			B3-GEO			B4-DIS			B5-WST		
	Limit state – interstory drift (%)														
	IO	LS	CP	IO	LS	CP	IO	LS	CP	IO	LS	CP	IO	LS	CP
Long period records	0.49	1.14	2.27	0.48	1.13	2.26	0.51	1.20	2.39	0.27	0.59	1.18	0.44	0.69	1.38
Short period records	0.49	0.78	1.55	0.48	0.75	1.50	0.51	0.81	1.62	0.27	0.32	0.64	0.44	*	0.78

*: LS limit state is close to the CP performance criterion, and hence it is eliminated

Acknowledgments

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