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Full Length Research Paper

Ductility demand of structures with vertical irregularities subjected to pulse-like ground motions

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The present paper addresses the seismic displacement ductility demand of structures with vertical irregularities when subjected to velocity pulse-like ground motions. Specifically, the irregularities are in strength, stiffness, and combined strength-and-stiffness in the first storey of structures. A nonlinear dynamic time history analysis was performed based on lumped mass shear-type multi-degree-of-freedom (MDOF) models and on eight near-fault pulse-like ground motions. The structural displacement ductility demand and its distribution were studied. The displacement ductility demand was found to be higher when accounting for vertical irregularities and velocity pulse effects. Furthermore, strength irregularities have more significant effects on the maximum inter-storey displacement ductility demand than those of combined strength-and-stiffness irregularities, while the effects of stiffness irregularities were different. In addition, the displacement ductility demands at the first storey increased by reducing only the strength or by simultaneously reducing the strength and the stiffness of this storey. However, in this case, displacement ductility demands decreased at other stories. Finally, reducing only the first storey stiffness leads to the decrease of all of the inter-storey displacement ductility demands.

Key words: Vertical irregularity, seismic, reinforced concrete frame, ductility, multi-degree-of-freedom systems, shear type.

INTRODUCTION

Vertically irregular structures make up a large portion of urban structures. Irregular structural schemes are often due to aesthetic, functional, and economical constraints. These irregular structural schemes result in the non-uniform distribution of mass, stiffness, and strength along the structure height, which may, in its turn, result in a concentration of stress and deflections or in an undesirable load path in the vertical lateral force-resisting system. Such irregularities have been recognized as one of the main causes of severe damage or poor performance of structures during earthquakes. Past experiences show that near-fault velocity pulse effects of ground motions have significant influence on structural seismic responses. Hence, investigating seismic responses of vertical irregular structures subjected to near-fault velocity pulse-like ground motions is a new challenge.

Previous studies (Bertero et al., 1978; Krawinkler et al., 2003) have shown that structures subjected to near-fault pulse-like ground motions have larger drift and strength demands as compared with structures subjected to common earthquakes. Recently, these ground motions have also been considered in AS/NZS standard (AS/NZS 1170.4 2004), which defined this effect as N (T, D).

The effects of vertical irregularities on the seismic linear and nonlinear responses of structures, especially in high-rise structures, have been extensively investigated in the last few decades (e.g., Chopra et al., 1973; Moehle, 1984; Wood, 1992; Valmundsson and Nau, 1997; Lu et

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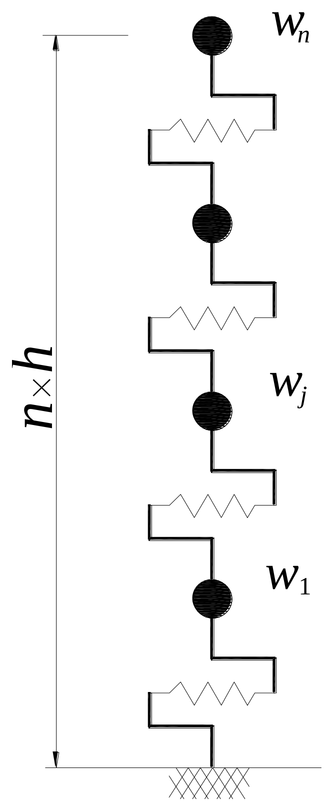


Figure 1. Lumped mass MDOF system model.

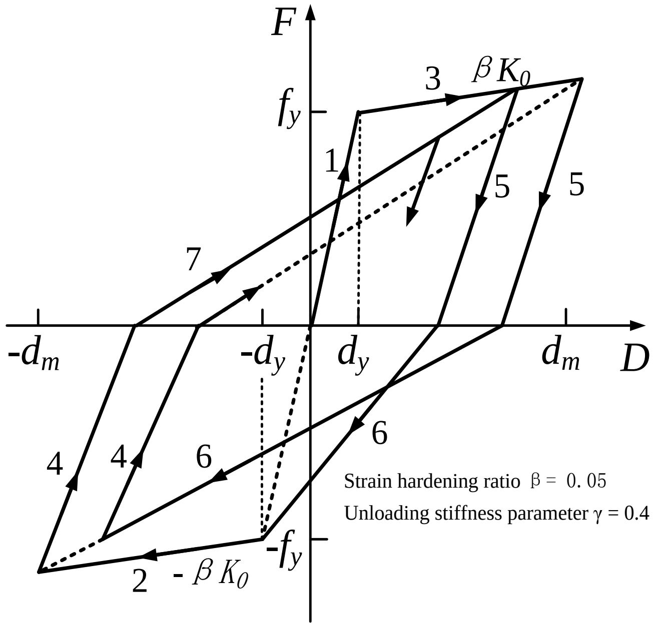


Figure 2. Modified clough hysteretic model.

al., 1999; Chintanapakdee and Chopra, 2004; Fragiadakis et al., 2006). Soni and Mistry (2006) and Zhou et al. (2009) comprehensively reviewed numerous studies on the seismic behavior of vertical irregular structures. Recently, this field of study has grown with the purpose of better understanding the behavior of such buildings. Although previous studies have produced qualitative information on irregularity effects, the velocity pulse effects of ground motions are seldom considered in seismic studies simultaneously. Vertical irregular layout and velocity pulse earthquake motion for structural design are two very disadvantageous design conditions in high earthquake intensity areas. Therefore, their combined effects are worth further study. At present, numerical simulation studies and experimental tests on this subject are rare, although independent research is adequate.

The objective of the present work is to study comparatively the effects of vertical irregularities on the ductility demands of structures subjected to near-fault pulse-like ground motions through a nonlinear time history analysis. Vertical irregular structures modeled as lumped mass shear-type multi-degree-of-freedom (MDOF) systems with 4, 8, and 16 stories are used. Irregularities in strength and/or stiffness are introduced by changing the properties of the first storey only. The effects of vertical irregularities on the maximum inter-storey displacement ductility demand and its distribution modes are evaluated.

STRUCTURAL MODELS

Reference regular structures

Reference regular structures are first designed according to Chinese seismic code (GB 50011) (2010). Shear-type models with heights of 4, 8, and 16 stories are used. In these models, each floor is considered as a lumped mass, connected by a link-spring element behaving as a modified Clough hysteretic rule. Examples of shear-type models are given in Figure 1. The modified Clough hysteretic rule is given in Figure 2.

In regular systems, the lateral stiffness of link-springs is assumed to be proportional to the equivalent static shear strength at each storey for lateral load distribution. The fundamental vibration periods T_1 are 0.4 s, 0.8 s, and 1.6 s for 4, 8, and 16 storey regular systems, respectively. A damping ratio of 0.05 is assigned for the first two modes, and the P-Δ effect of gravity loads is not included.

Vertical irregular structures

A structure is considered to be irregular if it has significant physical discontinuities in its configuration or in

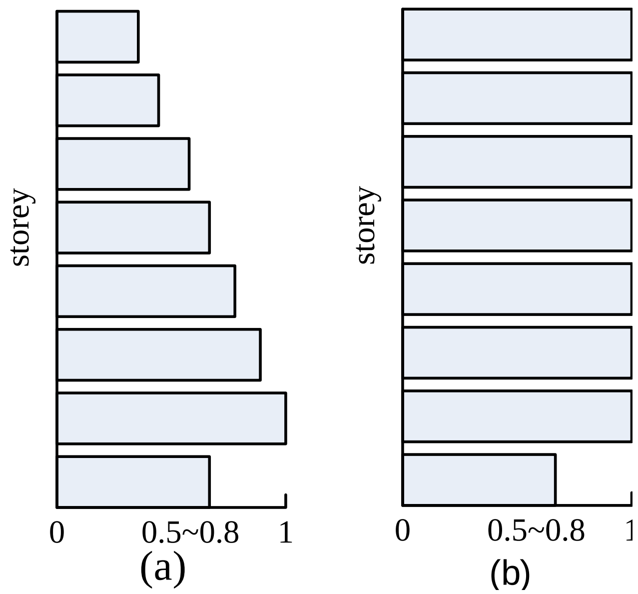


Figure 3. Distribution of vertical irregularities: (a) models used in the present study, and (b) models used in previous studies.

its lateral force-resisting system. Many structural codes in the world specify limited values for structural irregularities. Similar irregularities definitions are included in Chinese seismic code GB 50011 (2010). Three types of structural vertical irregularities are defined together with restrictions on analysis methods, except the case in which mass irregularity is not considered.

(1) Stiffness irregularity (soft storey): the lateral stiffness is less than 70% of that of the storey or less than 80% of the average stiffness of the next three stories above, except the top storey of building.
(2) Discontinuity in vertical lateral-force-resisting elements: The internal force of vertical lateral- force-resisting elements (column, seismic wall or seismic bracing) is transmitted downwards by the horizontal transfer member (beam or truss etc).
(3) Discontinuity in capacity (weak story): the storey lateral shear capacity is less than 80% of that of the next storey above. The storey shear capacity is the total capacity of lateral-force-resisting elements sharing the storey for the direction under consideration.

In the present study, three types of vertical irregularities are considered. These are strength irregularity, stiffness irregularity, and combined-strength-and-stiffness irregularity. The irregular structures are modeled by changing the irregular quantities only at the first storey of reference regular structures. This is considered the most severe yet practical case. As shown in Figure 3a, the irregular structures are obtained by reducing the strength and/or stiffness at the first storey to levels of 80, 70, 60 and 50% of that at the upper (second) storey, respectively. Contrary to models in previous studies, having constant strength and stiffness along the height (Valmundsson and Nau, 1997), the current paper employs analysis models for which stiffness and strength decrease with increasing height, which is closer to practical design.

METHODOLOGY

Input ground motions

The input ground motions are listed in Table 1 and scaled to provide target ductility. The upper and lower limits of the moment magnitude (M_w), closest source-to-site distance (R), and peak ground acceleration (PGA) for the large velocity pulse-like ground motions are $6.5 \leq M_w \leq 7.6$, R < 15 km and PGA > 75 cm/s, respectively. Pulse indicator (PI) takes values within 0.95–1.0, and is chosen to represent the largest velocity pulse ground motions (Baker, 2007).

Analysis

Both regular and irregular models are subjected to seismic excitations to conduct the nonlinear dynamic time-history analysis. Near-fault pulse-like ground motion records and the nonlinear structural analysis computer program Canny are used (Li, 2010). The analysis method consists of the following steps:

Step 1: Design a suite of lumped mass MDOF shear-type structures according to Chinese seismic code GB 50011(2010), defined as reference regular structures. Modify the first storey strength and/or stiffness to create structures with different types of vertical irregularities.
Step 2: Perform nonlinear dynamic time-history analysis on reference regular structures. Scale the intensity of selected ground motion from Table 1 until the maximum inter-storey displacement ductility is, within a 1% tolerance error, identical to the target ductility μ_t. Record the scaling factor.
Step 3: Conduct nonlinear dynamic time-history analyses on corresponding irregular structures using the same ground motion and same scaling factor in Step 2. Record the maximum inter-storey displacement ductility demand in irregular structures.
Step 4: Calculate the ratio of the maximum inter-storey displacement ductility demands in irregular structures in Step 4 to target ductility (the maximum inter-storey displacement ductility demand in regular structures).
Step 5: Select another ground motion from Table 1 and repeat Steps 2 to 4 until all earthquake records are used.

A total of 2,304 time history analyses are performed for the following permutations: eight ground motion records; irregular and reference regular MDOF systems with 4, 8, and 16 stories; three types of vertical irregularities of strength, stiffness, and combined strength-and-stiffness; irregularity degree levels of 80, 70, 60 and 50%; and target ductility ratios of 2, 4, 6, and 8.

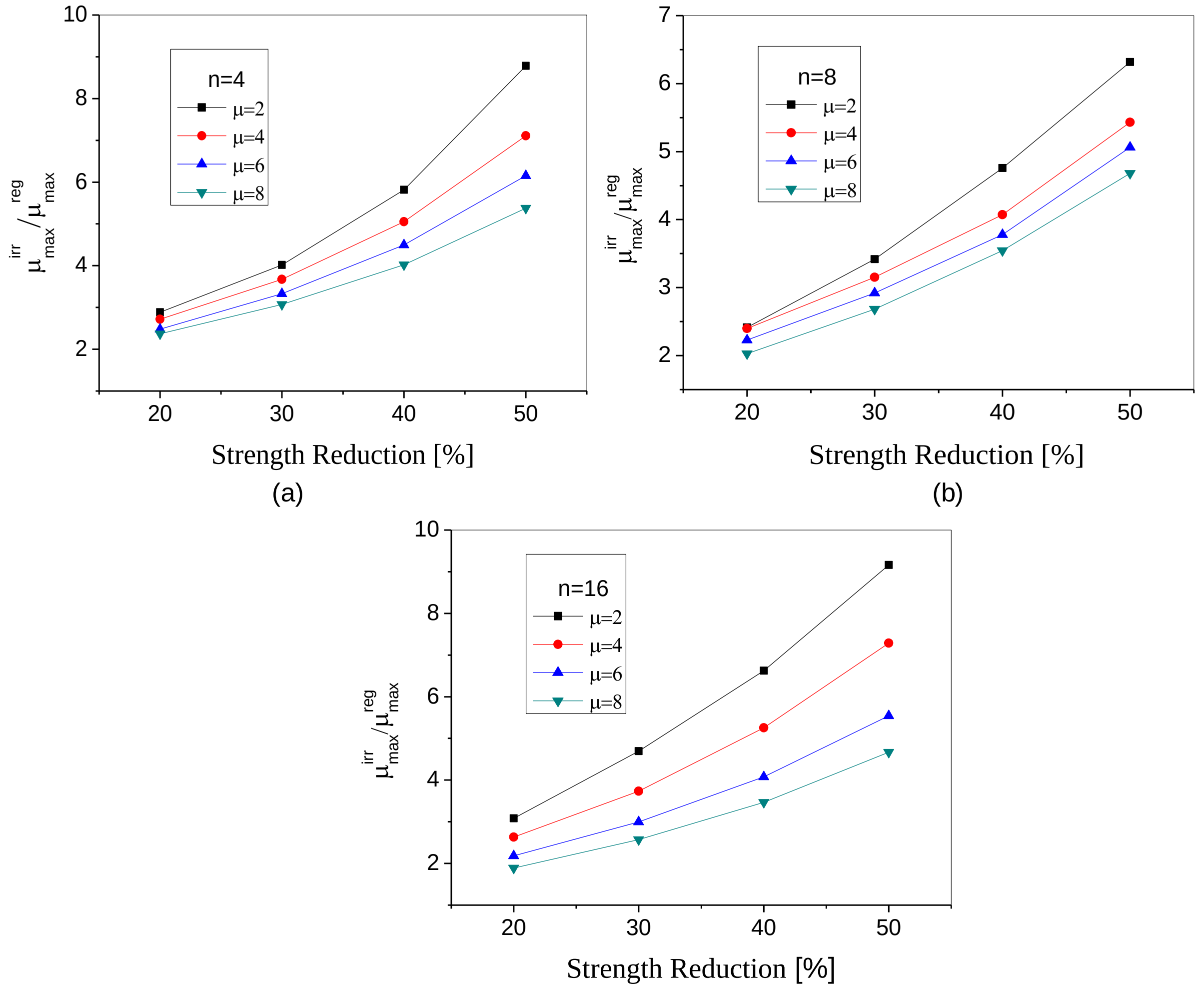
RESULTS AND DISCUSSION

Effects of strength irregularities

Figure 4 shows the variation of the maximum

Table 1. List of ground motions used in the present study.

Earthquake	Station	R (km)	M_w	PI	PGA (cm/s^2)	PGV (cm/s)
Chi-Chi, Taiwan	TCU128	13.2	7.6	1.00	183.45	78.7
Chi-Chi, Taiwan	CHY101	10.0	7.6	1.00	442.43	85.4
Erzican, Turkey	Erzincan	4.4	6.7	1.00	476.77	95.4
Imperial Valley-06	El Centro Array #7	0.6	6.5	1.00	453.22	108.8
San Fernando	Pacoima Dam	1.8	6.6	0.97	1407.74	116.5
Chi-Chi, Taiwan	TCU065	0.6	7.6	0.96	806.38	127.7
Landers	Lucerne	2.2	7.3	1.00	696.51	140.3
Kobe, Japan	Takatori	1.5	6.9	0.96	669.04	169.6



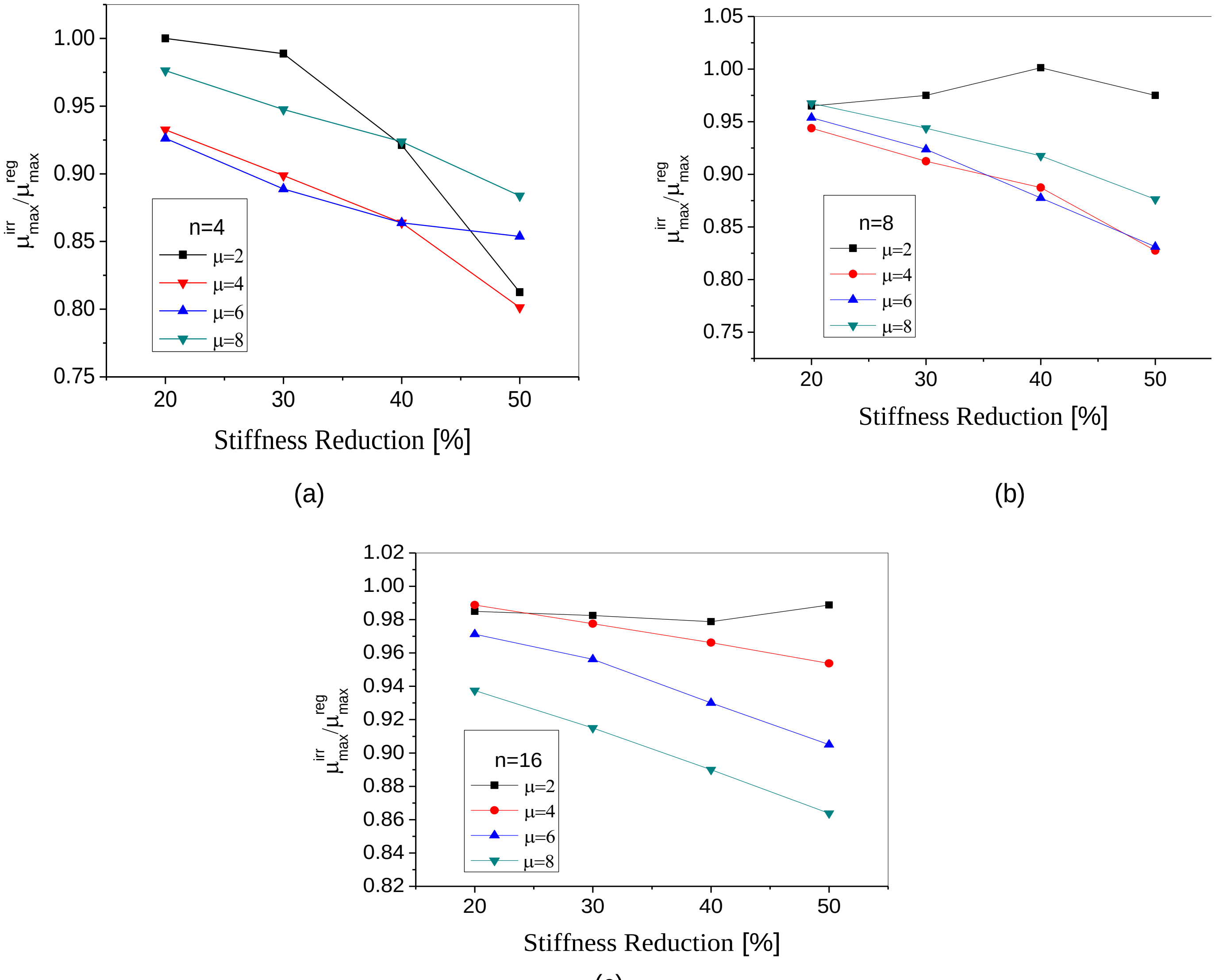
(a)

(b)

(c)

Figure 4. Effects of strength irregularities on maximum inter-storey displacement ductility demand: (a) 4-storey, (b) 8-storey, (c) 16-storey.

displacement ductility demand (MDDD). The MDDD is averaged over eight ground motions, for the cases when the first storey strength is reduced to certain levels of the upper (second) storey strength (80, 70, 60 and 50%). The results are presented as ductility ratios of irregular systems to regular systems (μ_{irr}/μ_{reg}). The MDDD always



(a)

(b)

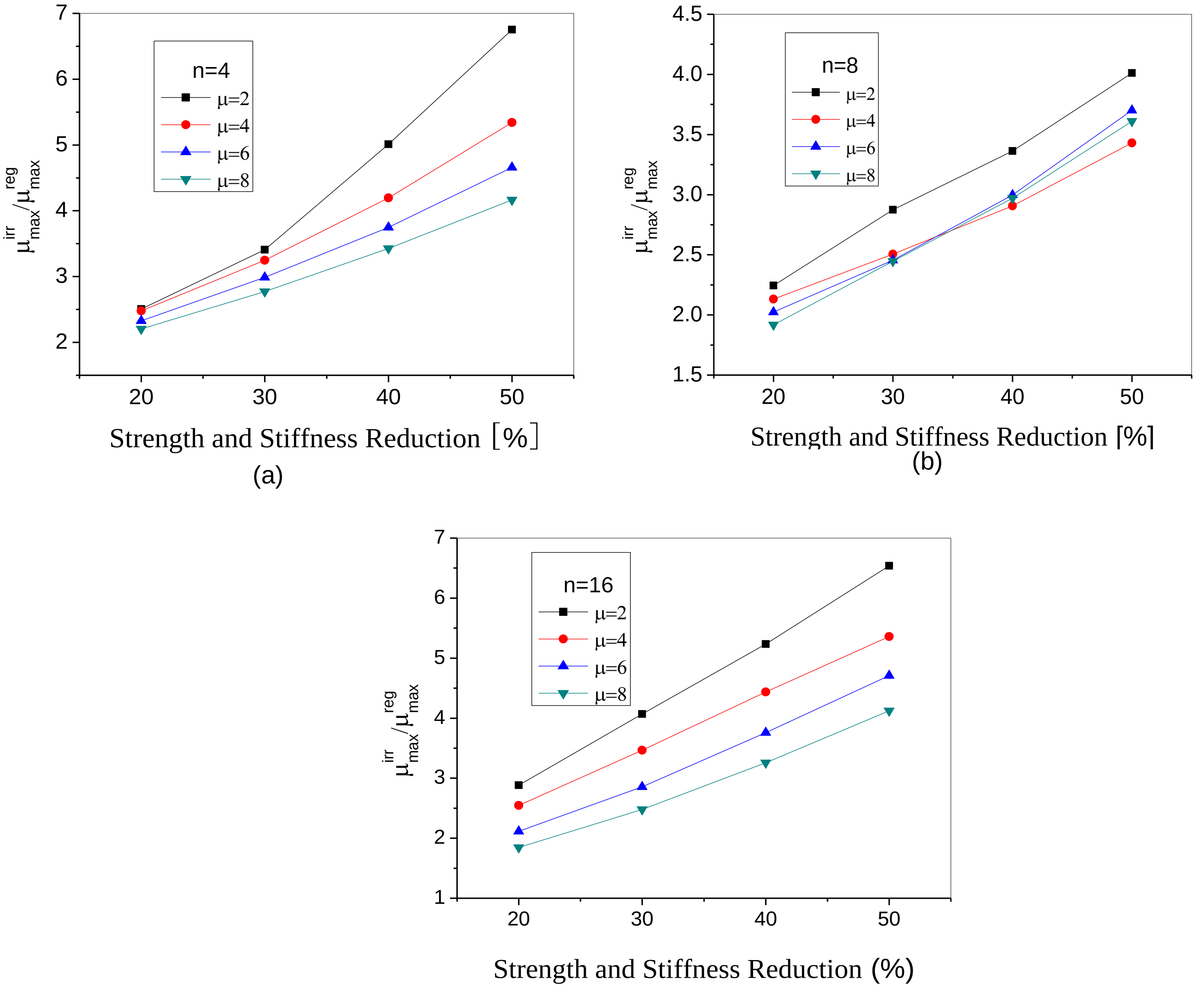
(c)

Figure 5. Effects of stiffness irregularity on maximum inter-storey displacement ductility demand: (a) 4-storey, (b) 8-storey, (c) 16-storey.

occurs at the first storey, and increases significantly with increasing strength reduction ratio for all structures. This has the same trend with a similar study (Valmundsson and Nau, 1997). For a 20% decrease in strength and depending on target ductility, the increase in MDDD is 140 –190%, 100–140%, and 90–210% for 4, 8, 16 storey structures, respectively. In the Valmundsson' study, MDDD increased by 80% for 5 storey structures, 100–130% for 10-storey structures, and 100–210% for 20 storey structures. Larger ductility demands are observed in the present study, although the structures have fewer stories. This may be largely due to the velocity pulse-like ground motions. This also illustrates those structures with irregular strength distribution exhibit larger ductility demands when accounting for velocity pulse effects.

Effects of stiffness irregularities

For the stiffness irregularities, the mean results of eight earthquake records are presented in Figure 5. When the target ductility of the regular system is higher (μ_t = 6 and 8), the MDDD decreases with increasing stiffness reduction ratio for all structures. The rate of increase of yield displacement with stiffness reduction is higher than that of maximum inter-storey drift. Therefore, the ductility demand decreases. When the target ductility is lower (μ_t = 2), the maximum decrease in MDDD decreases with



(a)

(b)

(c)

Figure 6. Effects of combined-strength-and-stiffness irregularities on maximum inter-storey displacement ductility demand: (a) 4 storey, (b) 8 storey, (c) 16 storey.

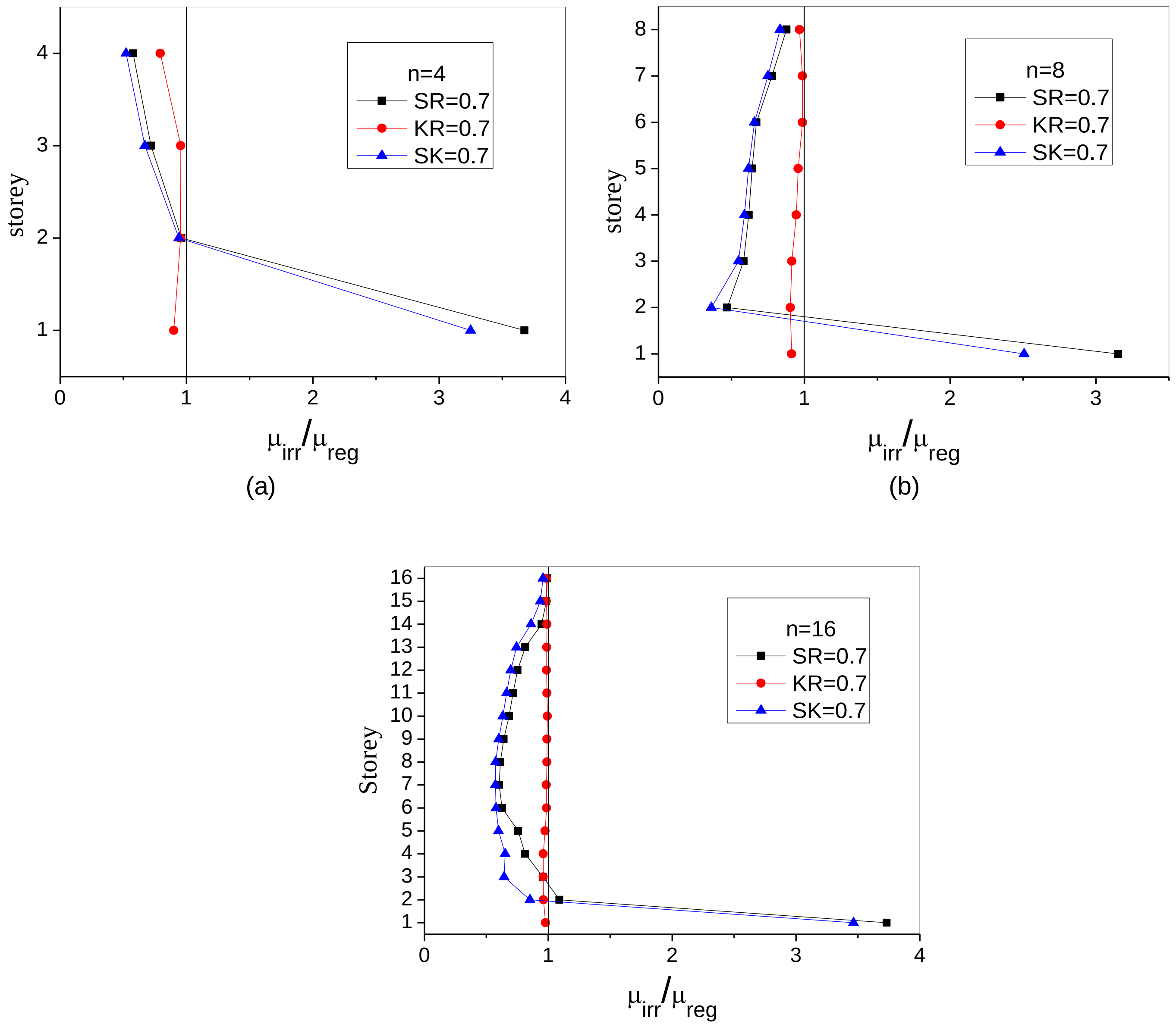
the increase of the number of storeys. The maximum decreases are 19.7, 3.5 and 2.1% for 4, 8, and 16 storey structures, respectively.

Effects of combined-strength-and-stiffness irregularity

Figure 6 shows that the MDDD markedly increases when the strength and stiffness at the first storey are simultaneously reduced. In contrast to cases with reduced strength, the increment of MDDD is lower in combined-strength-and-stiffness irregular structures because strength irregularities require larger ductility demand than stiffness irregularities. At a target ductility of 4, the MDDD increases by 230% for 4 storey structures, 150% for 8 storey structures, and 250% for 16 storey structures.

Effects of vertical irregularities on the distribution ductility demands

The effects of vertical irregularities on the distribution of structural ductility demands are also evaluated in the present study. For brevity, results presented herein are

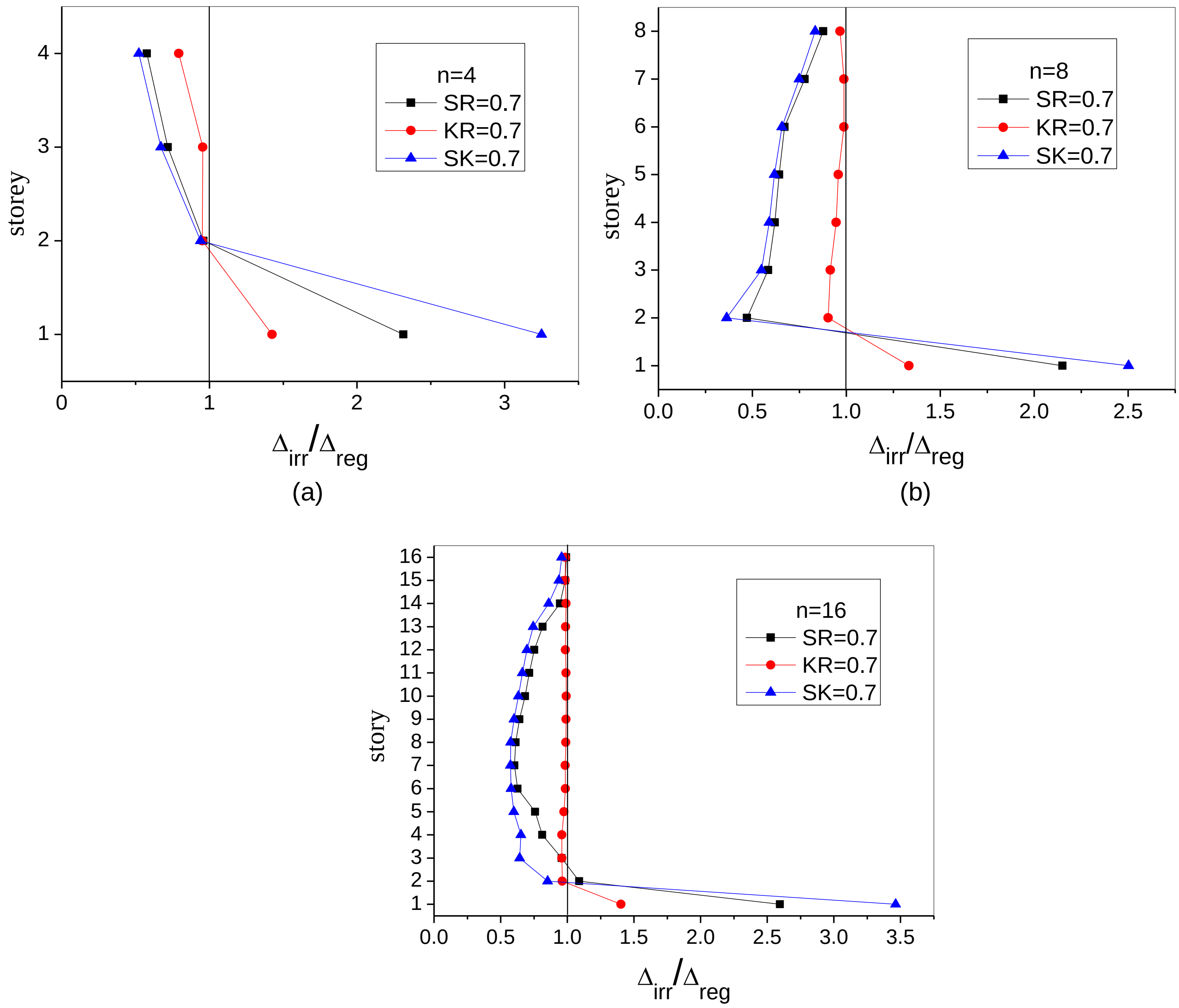


(a) (b) (c)

Figure 7. Effects of vertical irregularities on inter-storey displacement ductility demand distribution: (a) 4 storey, (b) 8 storey, (c) 16 storey.

only those obtained for the target ductility of 4, and the vertical irregularity of 70%. The vertical irregularities are denoted as SR for strength, KR for stiffness, and SK for combined-strength-and-stiffness.

Figure 7 shows all the ratios between inter-storey drift ductility demands of irregular systems to regular systems. The reduction of first storey strength markedly increases the drift ductility demand at the modified storey and decreases that of other stories. Contrary to cases with SR = 0.7, structures with SK = 0.7 have similar change trends in drift ductility demands. However, larger drift ductility demands are induced at the modified storey, whereas lower drift demands are needed at other stories. For stiffness irregularities, the reduction of first storey stiffness lowers all inter-storey drift ductility demands, which differs from the results obtained for the two other irregularity types mentioned above. Drift demands are analyzed to better understand this effect. As shown in Figure 8, vertical irregularities increase the modified storey drift demand and decrease drift demands in other



(a) (b)

(c)

Figure 8. Effects of vertical irregularities on inter-storey drift demand distribution: (a) 4 storey, (b) 8 storey, (c) 16 storey.

stories, which completely conforms to the results of Chitanapakdee (2004). The drift demand increment is larger in structures with SK = 0.7 than those with SR = 0.7. The smallest increments are observed in structures with KR = 0.7, at which the modified storey drift demand increases by 42, 33 and 40% for 4, 8, and 16 storey structures respectively. The drift demand decreases at all other stories. At the non-modified stories, the yield displacement holds constant because the stiffness and strength are not modified. Therefore, the displacement ductility demands (identical to the ratio of drift demand to yield displacement) at non-modified stories also decrease.

Conclusion

The current investigation of the effects of vertical irregularities on displacement ductility demands and its distribution modes in structures subjected to near-fault velocity pulse-like ground motions has led to the following conclusions:

1. Strength irregularities have the largest effect on the MDDD of irregular structures. The MDDD increases by 90–210% for 4, 8, and 16 storey irregular structures with 20% reduction in the first storey strength, depending on the storey number and target ductility. For structures with

identical stories, lower target ductility causes larger increments of MDDD in strength irregular structures compared with the reference structures. This has the same trend in displacement ductility demands with simultaneously reduced strength and stiffness. However, the increment is lower in contrast to cases with only reduced strength.

2. Reducing the first storey stiffness decreases the MDDD. At higher target ductility of 6 and 8, larger stiffness reduction ratios cause larger decreases in the MDDD for stiffness irregular structures. At a lower target ductility of 2, the largest increments of MDDD decrease with the increase of storey numbers.

3. Both cases of strength reduction and combined strength-and-stiffness reduction in the first storey increase the displacement ductility demands at the first storey and decrease those at other stories. For stiffness irregularities, the displacement ductility demands at all stories decrease with stiffness reduction. When stiffness is reduced at the first storey, the drift demand at the first storey increases, whereas the drift demands at the other stories decrease.

The preceding conclusions are based on an investigation of lumped mass shear-type MDOF structures, which may not be valid for other types of structures. Preliminary analysis shows that the intensity of velocity pulse-like ground motions and structural post-yield stiffness ratio influence the ductility demand of irregular structures. Such influence remains to be investigated in future work.

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