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Evaluation of combination rules for multi-story buildings with asymmetric set-backs

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Abstract. The effectiveness of 100/30, 100/40 and SRSS directional combination rules on the response of asymmetric setback buildings is examined. Because of the irregularity in setback buildings, the maximum seismic response would be correlative with the direction of earthquake. To verify the directional combination rules of mode superposition methods, the time history analyses of setback buildings to real earthquake records are carried out. Example analyses have been used to compare the validty and accuracy of SRSS and percentage methods for frame and dual frame-wall systems.

Keywords: combination rules; seismic analysis; multi-story buildings; asymmetric set-backs

1. Introduction

For architectural reasons many multistory buildings are designed with setbacks. Setback usually means discontinuity and termination of partial bending resistance members, which will lead to inappropriate load transfer and sudden change of lateral stiffness. The part of the structure above the setback level is identified as the tower and the part below as the base. To provide a tapering effect along the height, a building may have multiple setbacks, each starting at different levels. Depending on the location of the tower relative to the base, one can also classify setback buildings into buildings with symmetric setbacks and asymmetric setbacks.

In design, it is necessary to estimate the force distributions among the load-resisting elements when such structures are subjected to lateral loadings. Due to sudden change in stiffness at the setback, the load distribution is often complex in the neighborhood of the setback level. When the setback is asymmetric, further complication will arise due to the torsional effect. The good prediction of internal forces is important for seismic design of such buildings.

It is known that the excitation angle of the ground motion is one of the important parameters that directly affects the seismic demand on a building. Since analyzing a building with all possible excitation angles is impractical, combination rules have been used for design.

The critical orientation of the earthquake components as well as the ways of combining their

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individual effects have been of interest to the civil engineering profession. Penzien and Watabe (1975) stated that the three components of an earthquake are uncorrelated along a set of axes generally denoted as principal axes. The major principal axis is horizontal and directed toward the epicenter, the intermediate axis is horizontal and perpendicular to the orientation of the major component, and the minor principal axis is vertical. The critical response could be obtained when these components are applied. Rosenblueth (1980) stated "lack of correlation of the principal accelerograms insures that responses are also uncorrelated". Smeby and Der Kiureghian (1985) observed that, for response spectra analysis of linear structures, when the two horizontal principal components are not along the structural principal axes, the effect of correlation is small and that if the two horizontal components have identical or nearly identical intensities, then the effect of correlation disappears. Newmark (1975) and Rosenblueth and Contreras (1977) proposed the Percentage Rule to approximate the combined response as the sum of the 100% of the response resulting from one component and some percentage (β) of the responses resulting from the other two components. To combine the two horizontal components, Newmark (1975) suggested β to be 40% and Rosenblueth and Contreras (1977) suggested β to be 30%.

More recently, many other studies attempted to evaluate the effectiveness of combination methods for different types of structures. Gonzalez (1992) proposed a method that include earthquake directional effects on the seismic analysis of building. Three linear buildings with different structural characteristics were analysed considering actual earthquake acceleration records and acceleration response spectra, and acceleration design spectra. Reyes-Salazar *et al.* (2004), studied both the 30% and the SRSS rules by using time history analysis and complex multi-degree of freedom (MDOF) systems. Cacciola *et al.* (2004) proposed a simplified procedure for evaluation of correlation coefficients and peak factors consistent with the power spectral density of seismic excitation. The procedure is based on an approximate analytic expression for direct evaluation of the power spectral density of the excitation consistent with any prefixed response spectrum, and the evaluation of the consistent correlation coefficients and peak factors by using analytical expressions. Lopez *et al.* (2004) investigated the CQC3 response for determining the critical response of structures to two horizontal and the vertical seismic components with arbitrary design (or response) spectra. Gao *et al.* (2004) presented the methods of multi-component seismic response analysis for curved bridges. Because of the interaction between bending and torsion resulted from the irregular plane, the maximum seismic response of curved bridges would be correlative with the input angle of earthquake. The employable domain and limitation of SRSS3 method is well defined from the intensive study of CQC3 method and SRSS3 method. Salazar *et al.* (2004) performed a numerical study on steel frames by using nonlinear analyses. The numerical study indicates that The Square Root of the Sum of the Squares (*SRSS*) and the 30-percent (30%) combination rules may underestimate the combined effect. Li and Song (2004) presented a modal combination method for earthquake-resistant design of structures to multidimensional seismic excitations. With the assumption that an earthquake is a stationary random vibration, the correlation among the input components is considered in the proposed method. Maleki and Bisadi (2006) investigated the effects of seismic force direction on the responses of slab-girder skewed bridges in response spectrum and time history linear dynamic analyses and also examined the combination rules for orthogonal earthquake effects, such as the 100/ 30, 100/40 percentage rules and the SRSS method.

Rigato and Medina (2007) examined the influence of the ground motion for a single-storey structure subjected to bi-directional ground motions.

Lucchini *et al.* (2011) investigated the torsional response of a two-way aymmetric single-story building under biaxial excitations by using nonlinear dynamic analysis. In this study ground motions of increasing intensities, characterized by varying angles of incidence, were used to show the evolution of the seismic behavior with the increase of the inelastic demand.

Kostinakis *et al*. (2013) presented the effectiveness of the percentage combination rules for the determination of the maximum value of any response parameter under two horizontal seismic components within the context of linear response history analysis. They analized several reinforced concrete buildings subjected to eight bi-directional seismic motions and compared the maximum response values computed by the 100/30 and the 100/40 rule to the maximum response over all incident angles produced by analytical formulas. Muscolino *et al*. (2013) proposed a damping-adjusted combination rule for the response spectrum analysis of base-isolated buildings. Kostinakis *et al*. (2013) evaluated the selection of sectional forces needed for the design of R/C frames by means of nonlinear dynamic analysis. They designed a single-story building by using four different procedures based on the results of linear response history analysis. They performed nonlinear dynamic analyses under bi-directional ground motions for different seismic intensity. Fontara *et al*. (2015) investigated the influence of the orientation of the ground motion reference axes, the seismic incident angle and the seismic intensity level on the inelastic response of asymmetric reinforced concrete buildings.Cantagallo *et al*. (2015) investigated the impact of the earthquake incident angle on the structural demand and the influence of ground motion selection and scaling methods on seismic directionality effects. They evaluated seismic directionality effects by subjecting reinforced concrete structures to different scaled and un-scaled records oriented along nine incidence angles, whose values range between 0 and 180 degrees, with an increment of 22.5 degrees. Kostinakis *et al*. (2015) studied the combined influence of seismic orientation and a number of parameters characterizing the structural system of Reinforced Concrete (R/C) buildings on the level of expected damages. In this study it is reported that the damage level of the buildings is strongly affected by the incident angle of the ground motion.

The objective of this study is to investigate the effectiveness of 100/30, 100/40 and SRSS combination rules for design of setback buildings. Effectiveness is determined by comparing the obtained results with the exact results. The exact results in this study refers to the linear real ground motion analysis results.

2. Combination rules

Design codes generally specify two combination rules, β-percentage and SRSS respectively. Let R_x and R_y denote the response of interest due to the same ground motion acting along the structural axes X and Y, respectively. The β-percentage combination rule approximates R_c as the sum of 100% of the response resulting from the input in one direction and some percentage, β, of the responses resulting from the inputs in the other direction. The combination that yields the most critical estimate of the total response is used for design. Thus, in β-percentage combination rule the design response are taken as the larger of following

$$R_c = R_X + \beta R_Y \text{ or } R_c = \beta R_X + R_Y \qquad (1)$$

The most common percentage rules are the 100/30 (β=0.30) and 100/40 (β=0.40) rules. The 100/30 rule was developed by Rosenblueth and Contreras (1) and is considered in several codes. The 100/40 rule was proposed by Newmark and is now included in various codes e.g., ASCE.

According to the SRSS rule, the combined response is given by

$$R_c = \sqrt{R_X^2 + R_Y^2} \tag{2}$$

The basic assumption of the SRSS rule is that there is no correlation between the horizontal components.

The accuracy of the combination rules can be studied by comparing the results with the reference responses obtained from time history analysis. The above methods are all based on spectral mode superposition method. The maximum responses calculated by these simplified methods are approximate. It is necessary to compare the results with the exact results calculated by the time history analysis. The real earthquake records can be applied in time history analysis in order to verify these spectra based methods.

3. Case study

In order to investigate the effectiveness of combination rules on design of setback buildings numerical examples have been conducted for two different set of structural systems. The first set of buildings are frame systems, and the second set of buildings are dual frame-wall systems. In each set, 9 typical buildings with 8 stories and 5×3 bays are considered. The plan views and elevation of systems are depicted in Fig. 1.

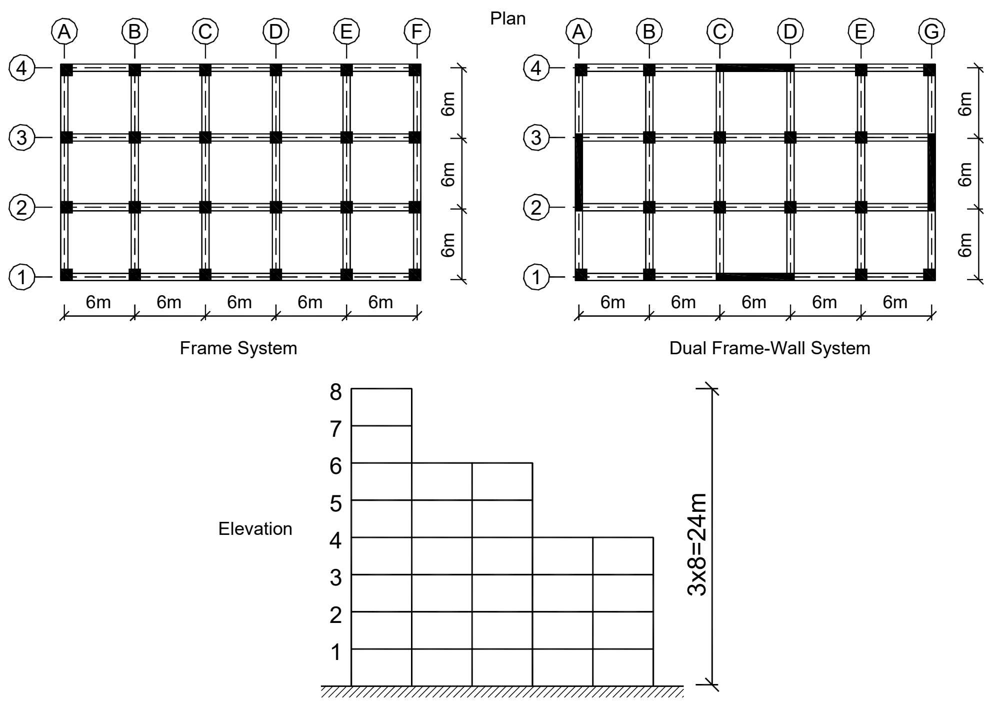

Fig. 1 Schematic floor plan and elevation of a typical set-back building

For the typical buildings the height of each storey is 3.0 meters and the spans of each bay are 6 meters in both directions. The dimensions of the structural elements are determined using a preliminary design process according to TS500 and Turkish Seismic Code 2007. The slab thickness is taken as 140 mm. The beam dimensions are (width/height) 250 mm/600 mm. Column dimensions of the building are 600 mm×600 mm for all columns of the lower 4 stories and 500 mm×500 mm for upper stories. In dual frame-wall systems the wall thickness is chosen as 250 mm.

Seismic parameters used in the analyses and the design of typical buildings are as follows, the expected earthquake ground motion is defined by TSC2007 design spectrum with an effective peak ground acceleration of 0.40 g (A_o=0.40), building importance factor I=1.0, behavior factor R=8 (high ductility level) for frame systems, R=6 for dual frame-wall systems. The soil class is assumed as a hard soil.

It is assumed that super dead load on slabs is 1.2 kN/m^2, and live load is 2.0 kN/m^2. An additional distributed load which represents the partition wall loads on beams is assumed 6 kN/m.

As shown in Fig. 2, one of the studied buildings correspond to buildings regular in elevation,

Table 1 Characteristics of the selected earthquakes

No	PEER Record No	Mag.	Year	Earthquake	Station	Site Class	PGA (g)	PGV (cm/s)
1	953	6.7	1994	Northridge	Beverly Hills- 14145 Mulhol	D	0.52	63
2	960	6.7	1994	Northridge	Canyon Country- W Lost Cany	D	0.48	45
3	1602	7.1	1999	Duzce, Turkey	Bolu	D	0.82	62
4	1787	7.1	1999	Hector Mine	Hector	C	0.34	42
5	169	6.5	1979	Imperial Valley	Delta	D	0.35	33
6	174	6.5	1979	Imperial Valley	El Centro Array #11	D	0.38	42
7	1111	6.9	1995	Kobe, Japan	Nishi-Akashi	C	0.51	37
8	1116	6.9	1995	Kobe, Japan	Shin-Osaka	D	0.24	38
9	1158	7.5	1999	Kocaeli, Turkey	Duzce	D	0.36	59
10	1148	7.5	1999	Kocaeli, Turkey	Arcelik	C	0.22	40
11	900	7.3	1992	Landers	Yermo Fire Station	D	0.24	52
12	848	7.3	1992	Landers	Coolwater	D	0.42	42
13	752	6.9	1989	Loma Prieta	Capitola	D	0.53	35
14	767	6.9	1989	Loma Prieta	Gilroy Array #3	D	0.56	45
15	1633	7.4	1990	Manjil, Iran	Abbar	C	0.51	54
16	721	6.5	1987	Superstition Hills	El Centro Imp. Co. Cent	D	0.36	46
17	725	6.5	1987	Superstition Hills	Poe Road	D	0.45	36
18	829	7.0	1992	Cape Mendocino	Rio Dell Overpass - FF	D	0.55	44
19	1244	7.6	1999	Chi-Chi, Taiwan	CHY101	D	0.44	115
20	1485	7.6	1999	Chi-Chi, Taiwan	TCU045	C	0.51	39
21	68	6.6	1971	San Fernando	LA-Hollywood Stro FF	D	0.21	19
22	125	6.5	1976	Friuli, Italy	Tolmezzo	C	0.35	31

without any setbacks. The other buildings have eight types of asymmetric-setbacks along height. In dual frame-wall system, in each direction, the walls are placed at the outer axis.

The models are excited by 22 recorded ground motions, as listed in Table 1. These ground motion records are the set of records used in ATC-63 Project as Far Field records. The properties of these records are, magnitudes are greater than 6.5 (M>6.5), distances are greater than 10 km (R>10 km), peak ground accelerations (PGA) are greater than 0.2 g and peak ground velocities (PGV) are greater than 15 cm/s.

During the analysis, damping of buildings is considered to be 5% of the critical damping. In order to capture the most unfavourable cases ground motions are applied to the buildings in angles, α, varying from 0° to 180° with increments of 6° and the maximum responses are obtained. The acceleration spectrum for each ground motion record is obtained, and these spectra are used in response spectrum method. To capture the effect of chosen reference axes for modelling the buildings, each building is rotated as θ=0°,30°,45°. The story shears and story displacements are obtained for these cases by using the combination rules mentioned above.

To compare the results, story shears and story displacements obtained by using 100/30, 100/40 and SRSS methods are compared to time history solution. Story shear and story displacement ratios are given in Fig. 4 to Fig. 20. The time history (TH) analysis results given in the figures are the average of 22 ground motion records and response spectrum method solutions are given with respect to reference axes angles. Story displacements are calculated at the center of mass of strories.

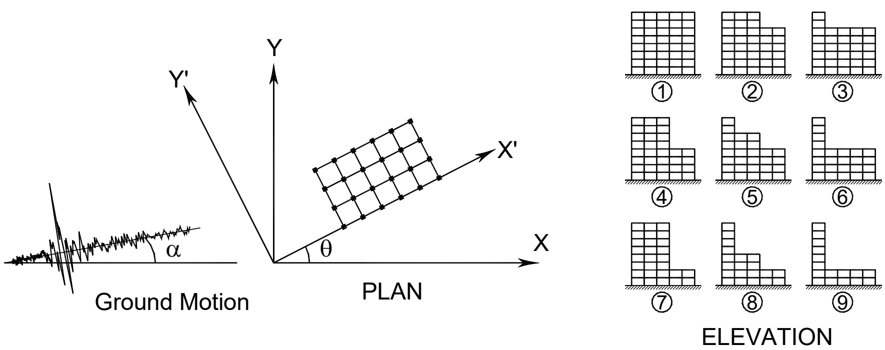

Fig. 2 Set-back building types

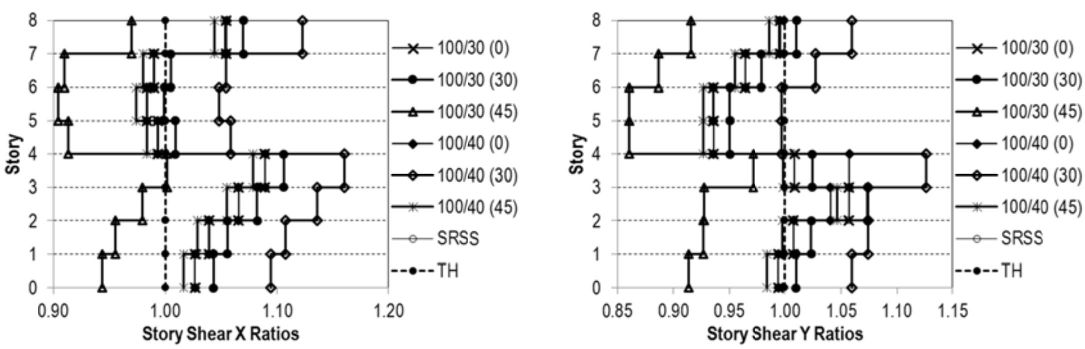

Fig. 3 Story Shear Ratios for X and Y Directions, Building Type 1

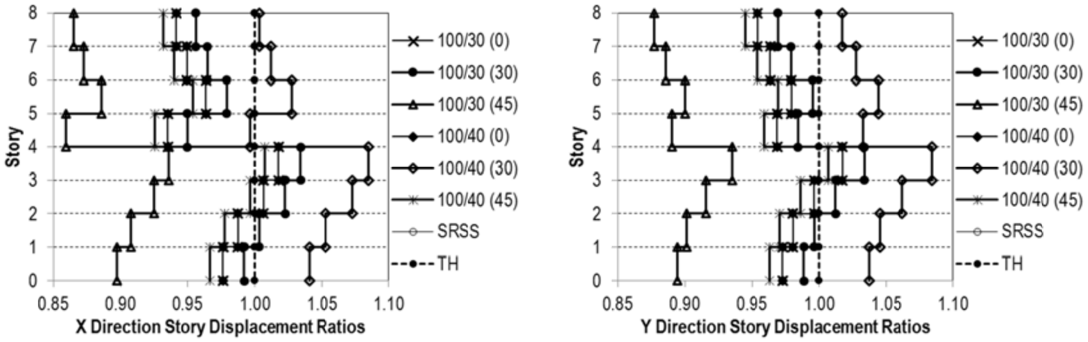

Fig. 4 Story Displacement Ratios for X and Y Directions, Building Type 1

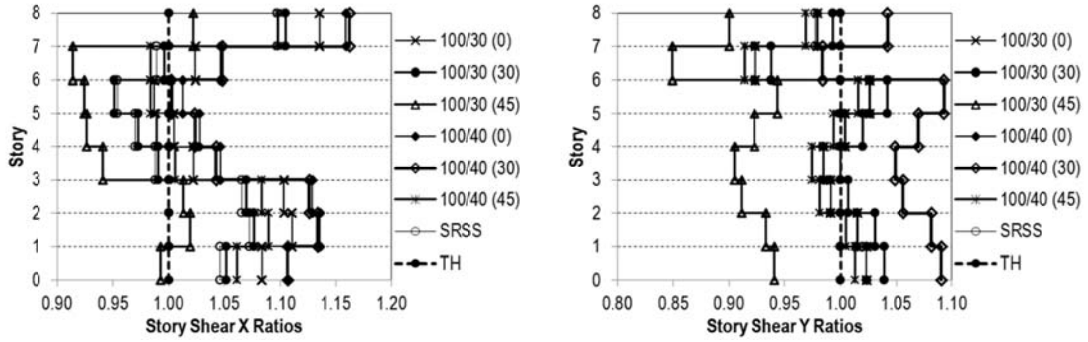

Fig. 5 Story Shear Ratios for X and Y Directions, Building Type 2

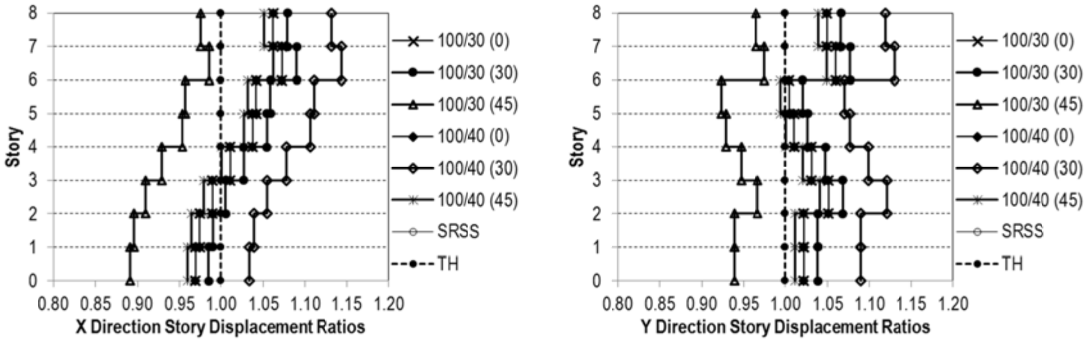

Fig 6. Story Displacement Ratios for X and Y Directions, Building Type 2

For building type 1 which has no setbacks, it can be observed from Fig. 3 and Fig. 4 that generally the maximum underestimations for both displacements and story shears are at the fifth story where the column dimensions are reduced. 100/40 generally gives highest overestimation.

For building type 2, it can be observed from Fig. 5 and Fig. 6 that generally the maximum underestimations for story shears are at seventh story where the setback starts. The highest underestimation is 15.1% (Story Shear Y) in 100/30 combination rule. 100/40 generally gives highest overestimation for both displacements and story shears.

For building type 3, it can be observed from Fig. 7 and Fig. 8 that generally the maximum underestimations for both displacements and story shears are obtained for 100/30 combination rule. Generally a change through underestimation is observed for displacement and story shear ratios at the vicinity of setback.

For building type 4, it can be observed from Fig. 9 and Fig. 10 that generally the maximum underestimations for both displacements and story shears are at the fifth story where the column dimensions are reduced and the setback starts. 100/30 combination rule generally gives highest underestimation.

For building type 5 which has stepped setback, it can be observed from Fig. 11 and Fig. 12 that generally the maximum underestimations for both displacements and story shears are obtained for

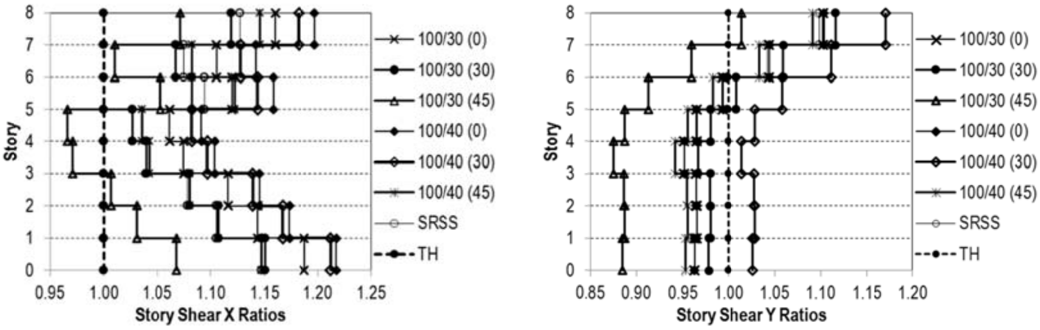

Fig. 7 Story Shear Ratios for X and Y Directions, Building Type 3

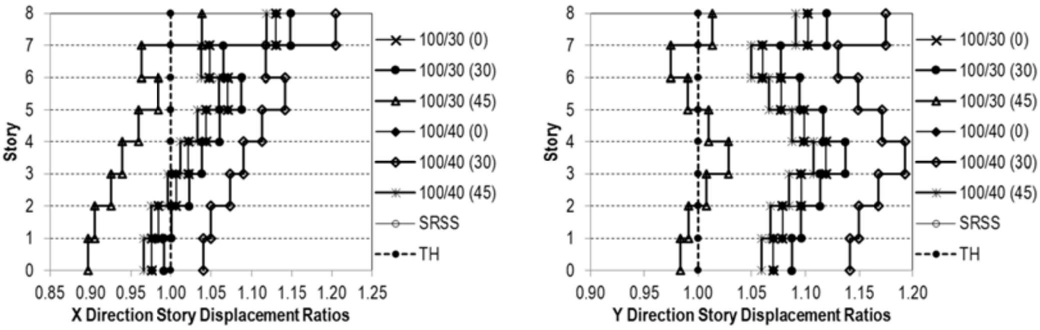

Fig. 8 Story Displacement Ratios for X and Y Directions, Building Type 3

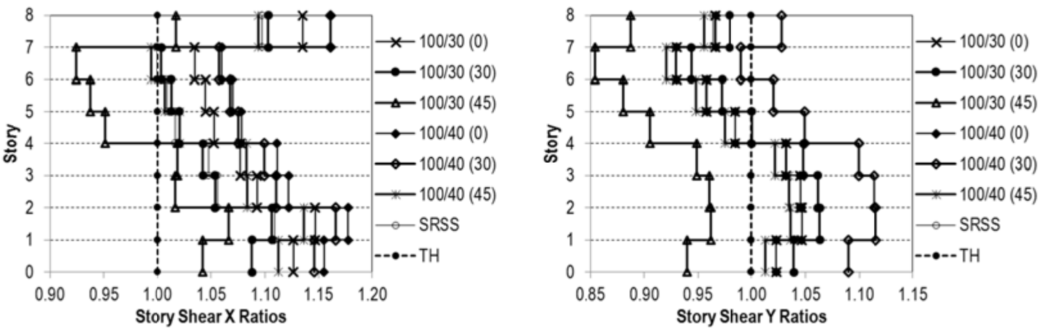

Fig. 9 Story Shear Ratios for X and Y Directions, Building Type 4

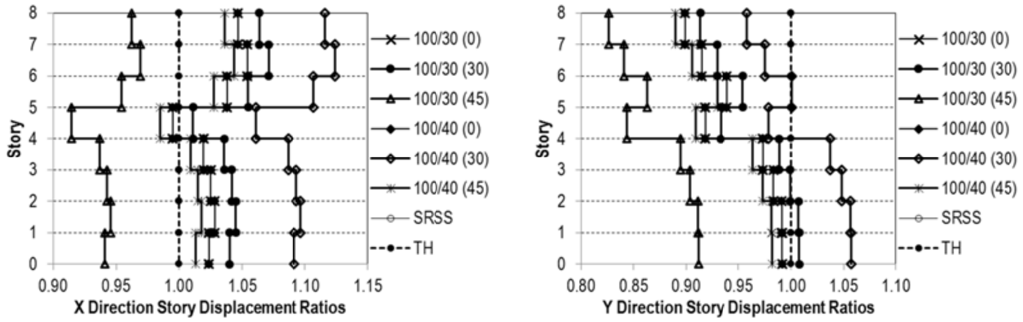

Fig. 10 Story Displacement Ratios for X and Y Directions, Building Type 4

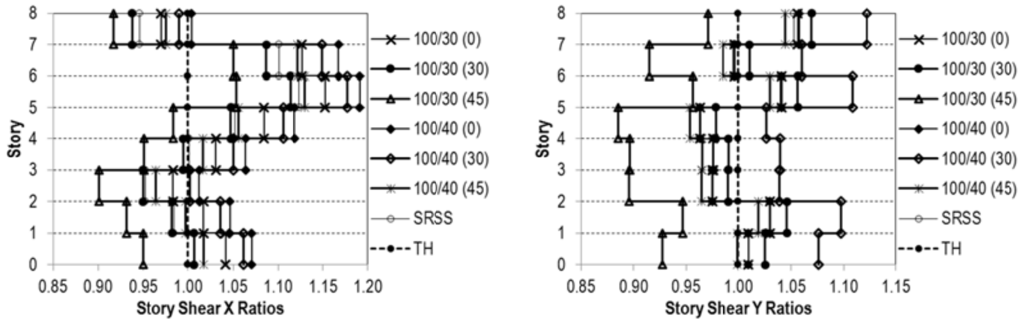

Fig. 11 Story Shear Ratios for X and Y Directions, Building Type 5

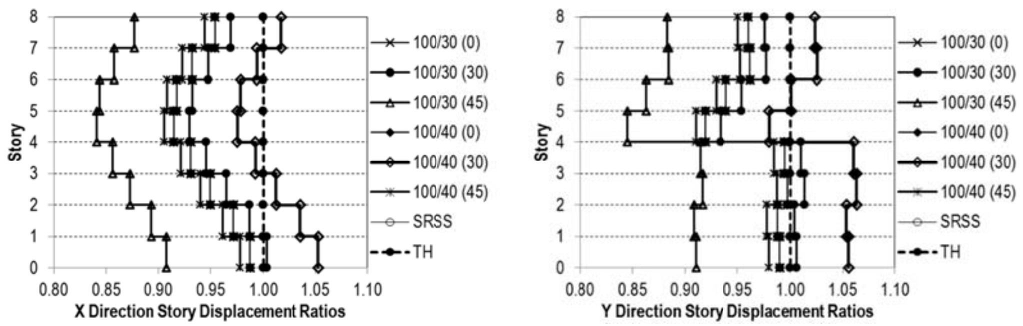

Fig. 12 Story Displacement Ratios for X and Y Directions, Building Type 5

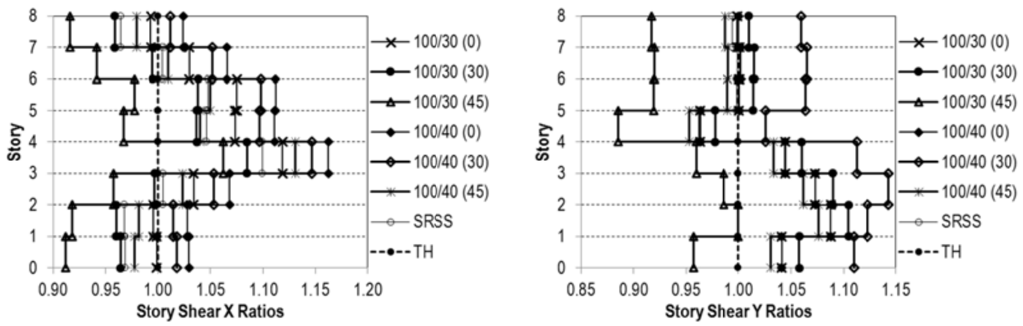

Fig. 13 Story Shear Ratios for X and Y Directions, Building Type 6

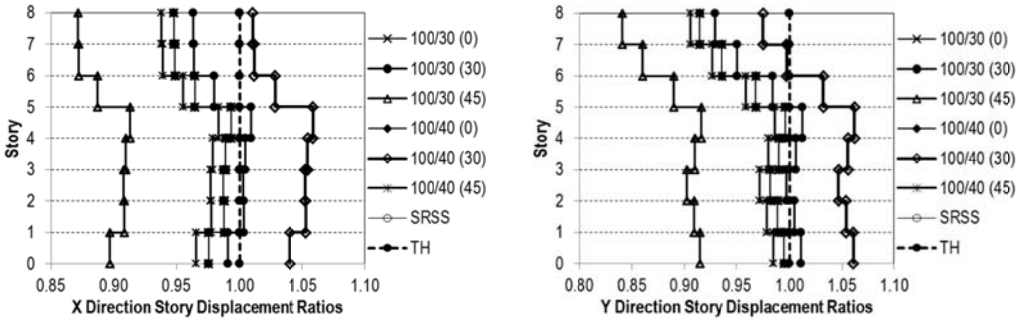

Fig. 14 Story Displacement Ratios for X and Y Directions, Building Type 6

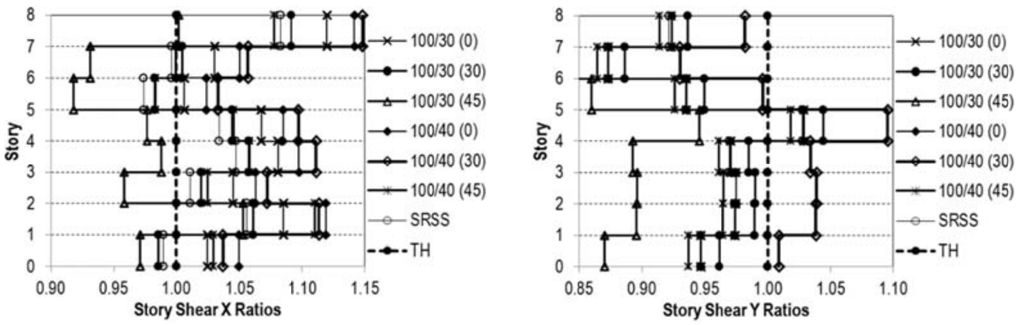

Fig. 15 Story Shear Ratios for X and Y Directions, Building Type 7

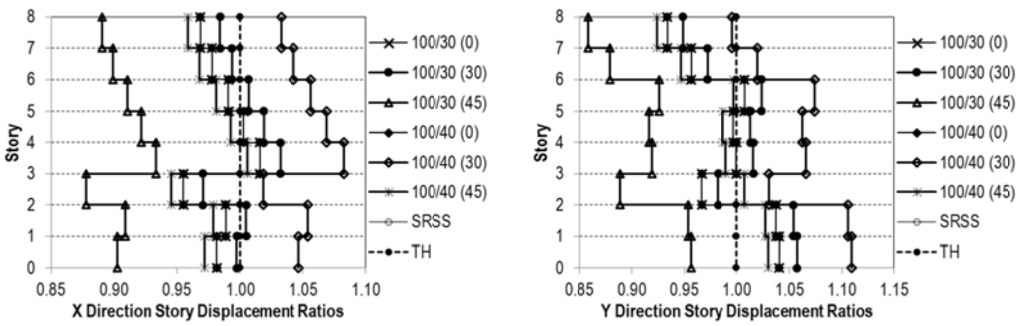

Fig. 16 Story Displacement Ratios for X and Y Directions, Building Type 7

100/30 combination rule. Generally a change through underestimation is observed for displacement and story shear ratios at the vicinity of setback.

For building type 6, it can be observed from Fig. 13 and Fig. 14 that generally underestimations for both displacements and story shears are starting at the vicinity of the setback. Since the shear wall at the outer right axis in plan is continous for only four stories and at outer left axis continous for eight stories, this causes additional torsional effects. For Y direction, this additional torsional irregularity effects the behavior of building. The response of the building can be explained as the increase in length and height of the setbacks results in greater reduction of mass and stiffness, thereby increasing the displacement demands. The abrubt change in the rigidity of lateral load resisting system in setback buildings leads to abrubt changes in shears at the setback level. This becomes more pronounced when shear wall are also cut off at the setback level.

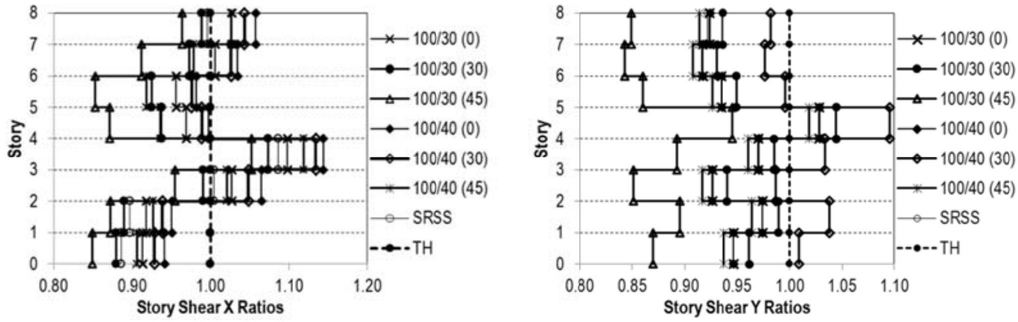

Fig. 17 Story Shear Ratios for X and Y Directions, Building Type 8

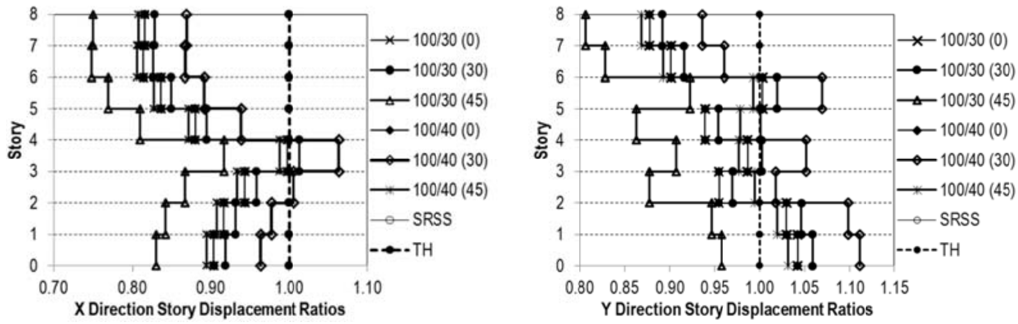

Fig. 18 Story Displacement Ratios for X and Y Directions, Building Type 8

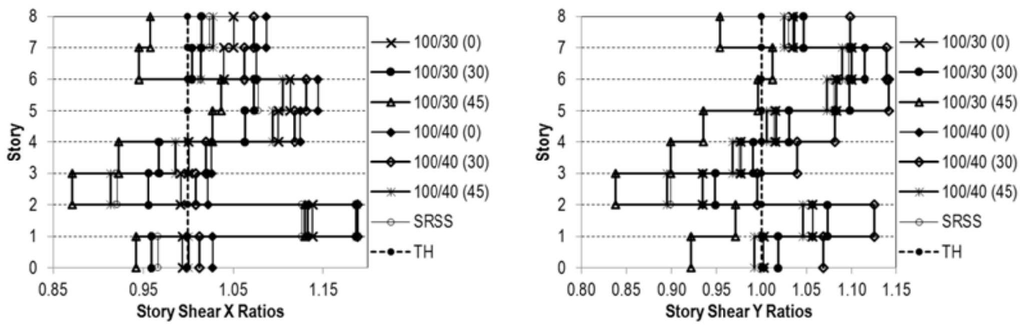

Fig. 19 Story Shear Ratios for X and Y Directions, Building Type 9

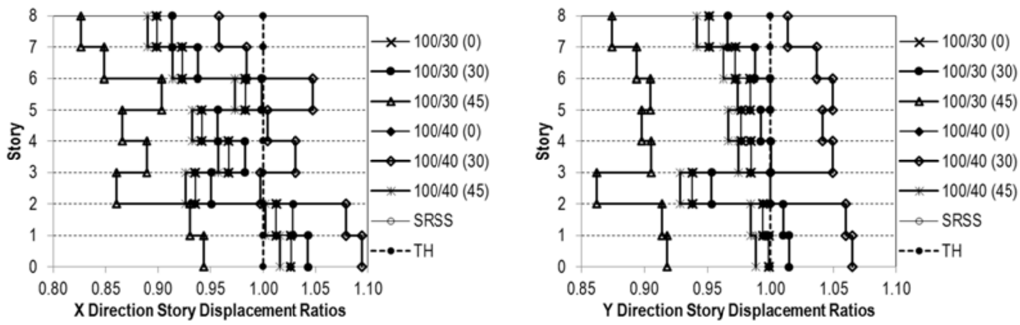

Fig. 20 Story Displacement Ratios for X and Y Directions, Building Type 9

For building types 7,8 and 9, a similar behavior is observed like building type 6.

The percentage of underestimation and overestimation for displacements and story shears are given in Table 1 to Table 4 for different combination rules.

It is observed from Figs. 3-20 that results obtained from the percentage rules depend upon the assumed orientation of the structural axes. If these axes are oriented differently from that shown in Fig. 1, different values for responses will be computed by the percentage rules. The critical orientation of the structure axes predicted by these rules can only be found by trial and error, requiring many dynamic analyses. There is not a single specific angle of incidence for each building which maximize response, and each response gets the maximum value of each of its response by a specific angle of incidence. This angle is not the same for various earthquakes.

Generally highest underestimations are observed in 100/30 combination rule. Among the combination rules 100/40 rule has the smallest probability of underestimation of story shears and displacements. In some cases 100/40 rule slightly overestimate the response.

Table 2 Maximum Relative Difference for Story Shears in X Direction

	Underestimation %			Overestimation %		
Type	100/30	100/40	SRSS	100/30	100/40	SRSS
1	9.55	2.61	1.69	10.60	16.05	8.86
2	8.58	1.66	4.57	13.52	16.23	9.70
3	3.39	---	---	18.73	21.72	14.68
4	7.58	0.59	0.04	14.68	17.76	10.87
5	9.94	3.59	5.39	15.25	19.12	12.33
6	*8.39	*2.05	*3.54	11.83	16.24	9.89
7	*8.20	*1.67	*2.63	11.97	14.81	8.25
8	*15.09	*9.42	*11.45	9.76	14.37	8.62
9	12.91	8.62	7.93	13.85	18.84	12.66

*Values are obtained from dual wall-frame system

Table 3 Maximum Relative Difference for Story Shears in Y Direction

	Underestimation %			Overestimation %		
Type	100/30	100/40	SRSS	100/30	100/40	SRSS
1	13.95	7.35	6.47	7.34	12.66	5.64
2	15.09	8.58	7.70	4.18	9.31	2.54
3	12.50	5.78	4.86	11.61	17.10	9.86
4	*14.53	*7.97	*7.10	6.30	11.53	4.63
5	*11.48	*4.68	*3.73	6.94	12.20	5.26
6	*11.49	*4.70	*3.79	10.45	14.31	8.70
7	*15.67	*9.22	*8.39	4.42	9.56	2.78
8	*17.15	*10.78	*9.87	3.44	8.53	1.81
9	*16.20	*10.51	*10.10	11.45	14.21	9.69

*Values are obtained from dual wall-frame system

Table 4 Maximum Relative Difference for Story Displacements in X Direction

	Underestimation %			Overestimation %		
Type	100/30	100/40	SRSS	100/30	100/40	SRSS
1	14.06	7.45	6.51	3.40	8.49	1.77
2	10.87	4.02	3.04	8.97	14.33	7.25
3	10.27	3.38	2.39	14.82	20.5	13.00
4	8.53	1.49	0.49	7.11	12.38	5.42
5	15.91	9.44	8.52	0.33	5.26	---
6	12.88	6.17	5.22	0.90	5.87	0.68
7	12.19	5.44	4.48	3.2	8.27	1.57
8	25.16	19.40	18.57	1.36	6.35	---
9	17.37	11.01	10.11	4.27	9.40	2.63

Table 5 Maximum Relative Difference for Story Displacements in Y Direction

	Underestimation %			Overestimation %		
Type	100/30	100/40	SRSS	100/30	100/40	SRSS
1	12.28	5.53	4.57	3.35	8.44	1.72
2	7.68	0.58	0.42	7.69	12.98	5.99
3	2.55	---	---	13.68	19.28	11.89
4	17.38	11.02	10.12	0.76	5.71	---
5	15.49	8.98	8.06	1.34	6.32	---
6	15.93	9.47	8.55	1.20	6.18	0.39
7	14.17	7.57	6.63	5.72	10.93	4.06
8	19.31	13.10	12.22	5.87	11.09	4.21
9	13.78	7.15	6.20	1.45	6.45	0.14

In case where setback that can be regarded as a vertical irregularity and torsional irregularity exists in a building, combination rules may underestimate displacement and story shears.

4. Conclusions

Setback usually means discontinuitiy and termination of partial bending resistance members, which will lead to inappropriate load transfer and sudden change of lateral stiffness. The nonuniform vertical mass distribution caused by setback may have a significant influence on the response to seismic loading. For asymmetric setback structure, torsion effect might be remarkable.

In this study the effectiveness of the combination rules, the 100/ 30, 100/ 40, and the SRSS method that are commonly used in the response spectrum analysis are examined. For this purpose nine buildings were analyzed. The lateral displacement and story shear response values produced by combination rules were compared to the time-history analysis results of setback buildings. Twenty-two ground motions records are selected and applied to the analytical models in various excitation angles.

While the numerical values are valid for the structural systems and ground motions used in the present study, the general conclusions can be expanded to all setback buildings. When compared with time history analysis results, the results of 100/40 percentage rule are reasonable, and in some cases are conservative. Thus , this paper suggests the use of 100/40 combination rule for the analysis of asymmetric setback buildings. And also the effect of different input angles cannot be neglected for seismic design of setback buildings. It may be not reasonable for the practical engineering design if this factor is neglected.

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