Seismic Performance Evaluation of Twisted Outrigger System

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SUMMARY

Complex-shaped tall buildings including twisted shape are frequently adopted as alternatives for the purpose of structural advantages as well as aesthetic. One of the remarkable features twisted façade is that it provides a good performance for wind load due to its aerodynamic property. In this paper, seismic performance of twisted outrigger system with 60 stories is examined. The seismic responses of the complex-shaped tall buildings are compared as the twisted angle varies. Three prototypes are assumed to be located in high seismicity zone, and in low seismicity zone for other three buildings. In a high seismicity area, it is found that the angle of twist is an important factor that affects story drifts and DCR.

Keywords: complex-shaped tall buildings, outrigger, twisted angle, story drift, seismic performance

1. INTRODUCTION

As a new tall building design trend, complex-shaped tall buildings have emerged since the late of the 20th century and is continuously employed up to date. The most noticeable feature in shape of complex-shaped tall buildings is that they are tapered; twisted and tilted. The simple and widely used structural system such as steel moment frames turned out to be inefficient for tall building design. Complex-shaped tall buildings are well recognized as an alternative to tall building design since they are advantageous in reducing wind load [1]. However, it is obscure to perform the seismic evaluation of complex-shaped tall buildings because no applicable standard has been established so far [2].
In this study, focusing on the twisted shape of a typical complex-shaped tall building, the authors would like to find the effects of the angle of twists to the seismic loads. Six of the 60 story buildings with outrigger system with internal braces are assumed to be located at the strong earthquake area and the moderate earthquake area [3]. The seismic performance evaluations are conducted as the twisted angle varies to check the changes story drifts and demand-capacity ratios.

2. PRELIMINARY STRUCTURAL DESIGN

2.1 Prototypes

The plan of the example buildings is shown in Figure 1(a). In elevation, the buildings have two outriggers (29-30F and 59-60F) and 14 brace groups in total (Figure 1(b)). As a strong earthquake area, Los Angeles in California is selected, and as a moderate earthquake area, Boston in Massachusetts is selected. Wind load and seismic load factors are like Table 3 and 4, respectively. Three models with different angles are assumed in each location: the first model, notated as OW00, has no plan angle change (Figure 2(a))

Table 1. Example Buildings

	CT60H-			CT60L-		
	OW00	OW15	OW30	OW00	OW15	OW30
Floors	60			60		
Location	Los Angeles, CA			Boston, MA		
Twisting Angle per story	0°	1.5°	3°	0°	1.5°	3°

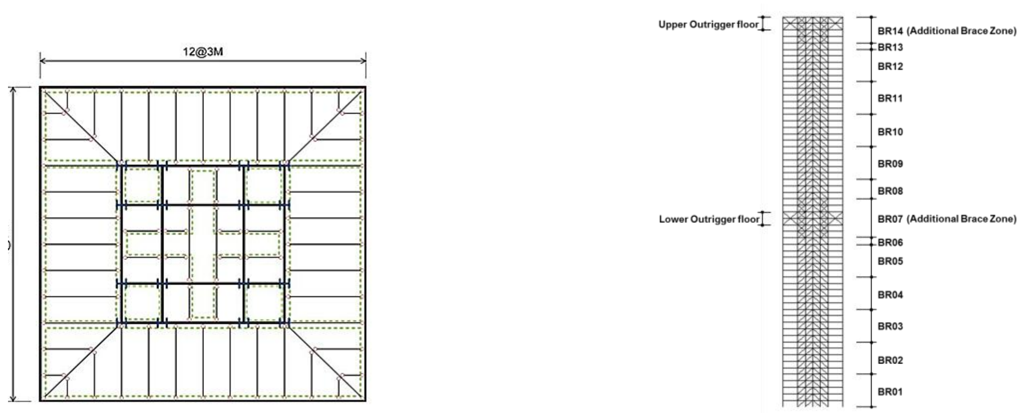
Table 2. Dimensions And Gravity Load

Structural Material	Steel
Story Height	3.9m
Building Height	234m
Plan Dimension	36m × 36m
Load on each slab	Dead load: 4.2kN/m^2 and Self-weight
	Live load: 2.5kN/m^2

so that it is not sorted as a complex shaped building; in the second model (notated as OW15), the plan of each story twists 1.5° to the same direction relative to the below level so that it makes 90° rotation at the top of the building (Figure 2(b)); and in the third model (notated as OW2), the plan of each story twists 3° to the same direction relative to the below level so that it makes 180°rotation at the top of the building (Figure 2(c)). With these configurations, each building is designed in accordance to its locational condition. The model nominations under given conditions are listed in Table 1. The commonly applicable building dimensions and the loads are shown in Table 2.

2.2 Design Loads

The load combinations follow ASCE 7-05 [4]. The wind speeds, category, and the important factor of the buildings for each location are shown in Table 3. Seismic Design Categories (SDC) and other information needed for the seismic design are also listed in Table 4. The Occupancy Category is assumed as Ⅱ. As it is indicated in ASCE 7-05, the response modification factor for "undefined steel system" is 3. Note that the R value for this kind of brace tube is not clearly defined yet in any standard.



(a) Plan (b) Section

Figure 1. CT60-OW00 building shapes

Table 3. Wind design factors

Area	Boston	Los Angeles
Wind Speed	100mph	85mph
Exposure	B	
Important Factor	1	

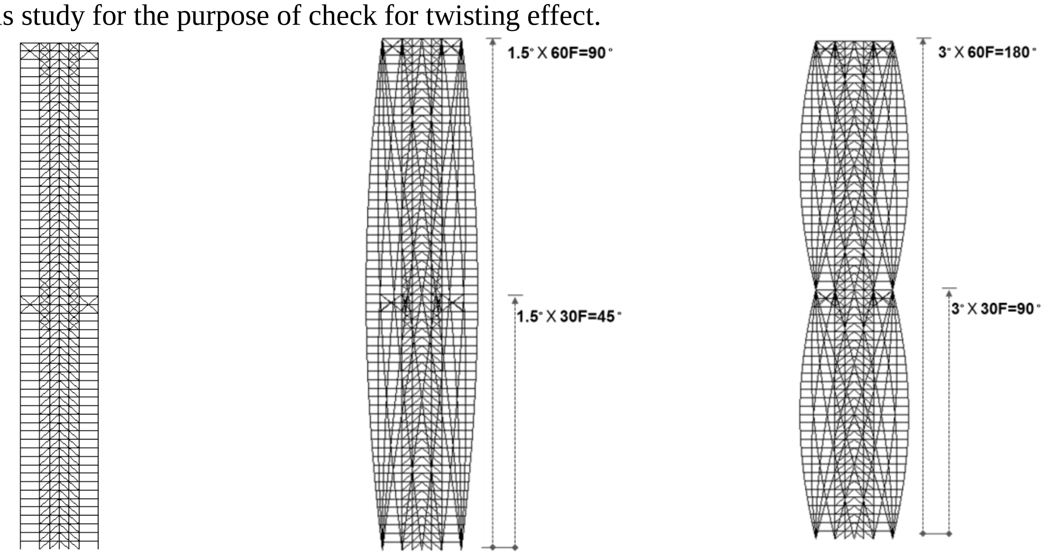
Table 4. Seismic design factors

Area	Boston	Los Angeles
Seismic Factors(g)	Ss=0.2g / S1=0.06g	Ss=1.5g / S1=0.6g
SDC	B	D
Soil Classification	D	
Important Factor	1	
Response Modification Factor	3	

2.3 Member Design

The member forces required to select member capacity is calculated according to ASCE 7-05, except that lower boundary of design acceleration for buildings with long period is not applied. A commercial program ETABS® is used for structural analysis purpose.

Seismicity and the twisted angles are the main parameters in this study. To represent buildings in the moderate seismic area, CT60L-OW00, CT60L-OW15 and CT60L-OW30 are used with twisted angles. To take twisting effect into account, wind load is assumed to be reduced due to twisting. This effect is accounted by using same member size of OW15 and OW30 as OW00. In strong seismic area, CT60H-OW00, CT60H-OW15 and CT60H-OW30 represent the complex-shaped tall buildings in the high seismic area with twisted angles. Assuming that prototypes in Los Angeles are governed by seismic force, it’s desirable to design members of three types differently. However, same members are applied to three types in this study for the purpose of check for twisting effect.



(a) CT60-OW00 *(b) CT60-OW15* *(c) CT60-OW30*

Figure 2. Outrigger System configurations

Table 5. Maximum Drift (CT60L, Boston) and inter-story drift ratio (CT60H, LA)

	CT60L- (Wind)			CT60H- (Seismic)		
	OW00	OW15	OW30	OW00	OW15	OW30
Drift	0.46m	0.64m	0.80m	0.009	0.0094	0.0103

Table 6. Fundamental Natural Periods (sec)

	CT60L-			CT60H-		
	OW00	OW15	OW30	OW00	OW15	OW30
Natural Period	5.61	5.89	6.19	5.30	5.56	5.85

When designing the members, the maximum allowable deflection of the building is assumed within the H/500, where H is building height. The strength check for each member is conducted based on ANSI/AISC 360-05 [5]. To meet the requirement of occupancy category in ASCE 7-05, the building is designed not to exceed 2% of the story drift ratio after the response spectrum analysis. Round HSS is used for brace members and square HSS is selected for column members. All steel members are grade 50W.

2.4 Result of Elastic Design

For CT60L models, member design is governed by stiffness rather than strength. The non-twisted building in Boston (CT60L-OW00) satisfies H/500 (0.468m) requirement. Boston example buildings with twisted angles (OW15 and OW30) exceed the limitation (Table 5). Meanwhile, member design of Los Angeles buildings is dominated by seismic force, so that maximum inter-story drift ratio is within maximum allowable drift ratio. As twisting angle increases, drift also tends to increase. This tendency is also reflected in fundamental natural periods of buildings are shown in Table 6. As it is common in high-rise buildings, the models have relatively long periods. In both area, with increments of the angle, the periods of the building increase. This means the higher of the angle, the lower stiffness of the building.

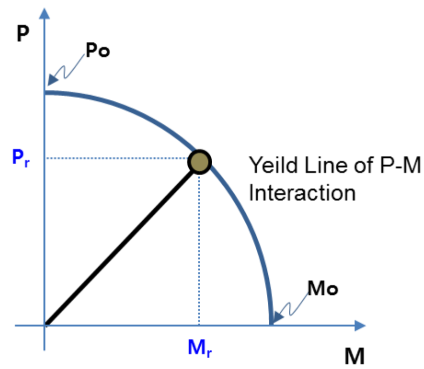
3. Nonlinear Response History Analysis

3.1 Nonlinear Model

To perform nonlinear seismic analysis, Perform 3-D® [6] is used. The nonlinear response history (NLRH) analysis is adopted to evaluate the response of the high-rise building under as realistic condition as possible. Elastic viscous damping ratio is assumed as 2.5% when NLRH analysis is conducted.

To check yield status in each member, elastic-perfectly plastic (EPP) option is selected. As shown in Figure 3, columns, outrigger members and the braces are modelled to receive both axial forces and moment with FEMA column type [7]. Although diagonal members including outriggers and braces are governed mainly by axial force component, to decide if each member enters the plastic range due to the influence of bending moment, the P-M-M interaction model is used. Axial capacity is calculated with respect to buckling strength suggested by ANSI/AISC 360-05.

(a) Chord Rotation Model (P-M-M model)

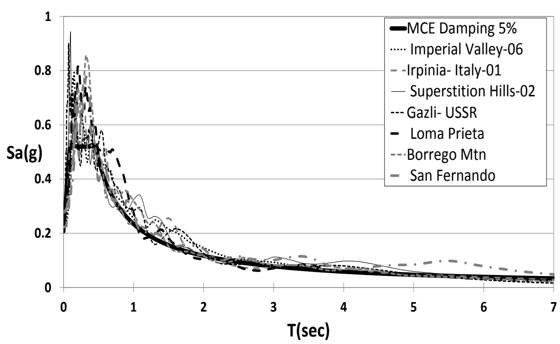


(b) P-M Interaction Curve

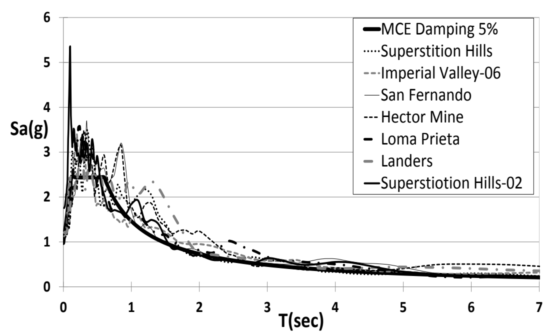
Figure 3. Nonlinear Element Model

3.2 Ground Motion Selection

The seismic wave to apply is selected from PEER Ground Motion web page [8]. As it's recommended in ASCE 7-05, maximum considered earthquake (MCE) level with 5% damping is selected for target spectrum. Seven pairs of the most similar ground motions as target spectrum are chosen for analysis and scaled in order to match target spectrum (Figure 4) using Geo-mean method [9]. It is also important to check if the square root of the sum of the squares (SRSS) of the fault-normal and fault-perpendicular spectrum is no less than the target spectrum especially between 0.2T and 1.5T. The average value of the selected seismic waves is used following the ASCE 7-05 recommendation.



(a) Target spectrum in Los Angeles



(b) Target spectrum in Boston

Figure 4. Target spectrum in each seismic area

4. Results of NLRH

4.1 Story drift ratio

The averages of the story drifts according to seven selected earthquakes are compared in Figure 5. It is recommended that the story drift ratio not be exceed 0.045 regardless of the seismic effect [10]. The story drifts in both areas satisfy this limitation. Due to the higher seismicity, the Los Angeles models (CT60H) show higher story drift ratio than the one in Boston. When it has higher angle of twist, the building stiffness decrease and as a result, the average story drift ratio increases. In Boston models (CT60L), the tendency is similar to Los Angeles cases.

Also, drift near outrigger floors is observed to be significantly reduced. It shows the effect of outrigger system.

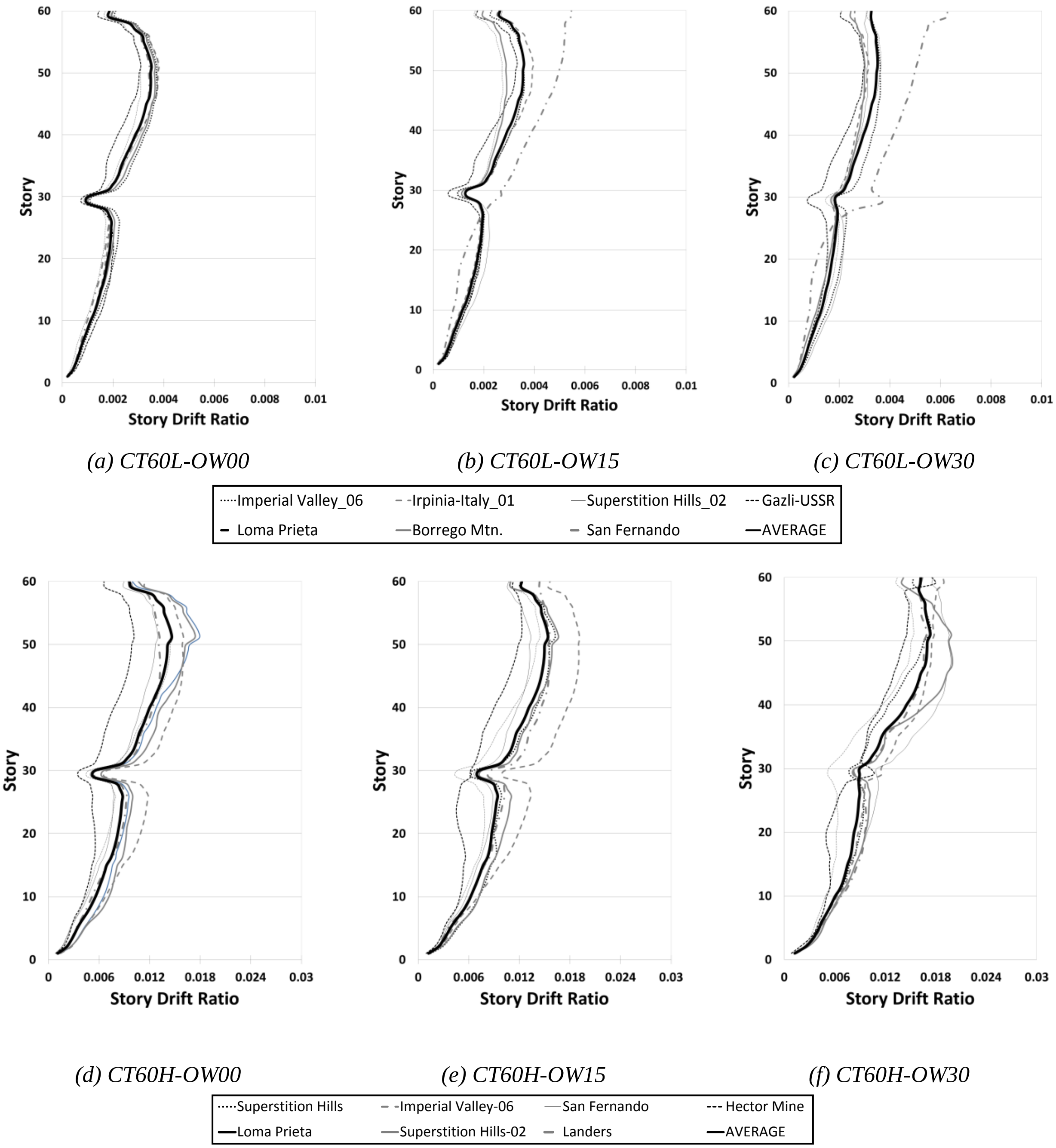


Figure 5. Story drift ratio of CT60L-(a, b and c) and CT60H- (d, e and f) after NLRH

Table 7. DCRs per diagonal members

Member	Story	*CT60L-*			*CT60H-*		
		OW00	OW15	OW30	OW00	OW15	OW30
BR01	1F-5F	0.10	0.23	0.27	0.57	0.88	0.91
BR02	6F-10F	0.07	0.22	0.25	0.51	**1.12**	**1.23**
BR03	11F-15F	0.06	0.20	0.21	0.45	0.98	**1.30**
BR04	16F-20F	0.05	0.19	0.19	0.42	**1.10**	**1.15**
BR05	21F-25F	0.05	0.18	0.15	0.33	0.93	0.79
BR06	26F	0.06	0.17	0.13	0.27	0.62	0.64
BR07	27F-32F	0.21	0.34	0.36	**2.64**	**2.83**	**3.86**
BR08	33F-35F	0.09	0.19	0.23	0.35	0.48	**1.43**
BR09	36F-40F	0.07	0.19	0.29	0.34	0.45	**2.37**
BR10	1F-45F	0.05	0.14	0.16	0.28	0.33	**2.00**
BR11	46F-50F	0.05	0.11	0.11	0.27	0.27	**1.26**
BR12	51F-55F	0.04	0.08	0.07	0.51	0.53	0.69
BR13	56F	0.04	0.05	0.03	0.19	0.19	0.33
BR14	57F-60F	0.08	0.15	0.17	0.64	0.44	**2.52**
OUTRIGGER	29~30F	0.04	0.05	0.04	0.21	0.21	0.45
	59~60F	0.03	0.04	0.05	0.37	0.39	0.50

4.2 Demand-Capacity ratio

Demand-Capacity Ratios (DCRs) are also important factor for seismic performance evaluation so that two types of diagonal members including braces and outrigger members are checked, shown in Table 7. DCR of each group represents peak value of a member in the group and the member ratio is estimated by average from seven ground motions.

Diagonal members are critical in lateral resistance so that these members are considered as force-controlled behaviour [10]. Therefore, DCRs are calculated based on yield point. As expected readily, CT60L-models show low DCRs for seismic force since main design factor is wind force. In case of CT60H-models, high seismicity result higher DCRs than CT60L-models. In particular, braces in lower outrigger floors are significantly affected to seismic force. DCRs tend to increase according to twisting ratio.

5. Conclusion

The effects of planar angle of twist, one of the frequent features in complex-shaped tall buildings, are examined under high and moderate seismic loading conditions. Through the elastic analysis, it is found the maximum deflections and natural fundamental periods increase as the stiffness of the building decreases with the existence of the angular changes. Conducting the nonlinear analysis, it is also found that the increments of the angle cause the decrease of the stiffness resulting in the change of story drifts. In tube framed complex-shaped tall buildings, the planar change of the angle is one of the important factors that affect the whole stiffness of the building.

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REFERENCES

[1] Y. Tamura, H. Tanaka, K. Ohtake, M. Nakai, Y. Kim (2010), *Aerodynamic Characteristics of Tall Building Models with Various Unconventional Configurations*, 2010 Structure Congress, ASCE.

[2] K. S. Moon (2010), *Stiffness-based design methodology for steel braced tube structures: A sustainable approach*, Engineering Structures, vol. 32, pp. 3163-3170.

[3] K. S. Moon (2012), *3rd Year Research Report*, Cutting-edge Urban Development Program, Korea.

[4] American Society of Civil Engineers, *ASCE/SEI 7-05 Minimum Design Loads for Building and Other Structures*, ed. Reston, VA: ASCE, 2006.

[5] American Institute of Steel Construction (2005), *ANSI/AISC 360-05 Specific for Structural Steel Buildings*, ed. Chicago, IL: AISC.

[6] CSI (2006), Perform-3D User Guide, Berkeley.

[7] CSI (2006), PERFORM Components and Elements, Berkeley, CA.

[8] PEER. Available: http://peer.berkeley.edu/peer_ground_motion_database

[9] Jack W. Baker and C. Allin Cornell (2006), *Spectral shape, epsilon and record selection*, Earthquake Engng Struct. Dyn.; 35:1077–1095.

[10] PEER (2010), *TBI Guidelines for Performance Based Seismic Design of Tall Buildings*. Berkeley, CA: PEER.