3D TEMPORAL CHARACTERISTICS ANALYSES FOR SEISMIC RESPONSES OF STRUCTURES

Junwu DAI[1], Xiaozhai QI[1], Yanru WANG[2], George C. LEE[3] and Mai TONG[4]

[1] *Professor, Institute of Engineering Mechanics, Harbin. China*
[2] *Ph.D Student, Institute of Engineering Mechanics, Harbin. China*
[3] *Professor, MCEER, State University of New York at Buffalo, USA*
[4] *Senior Scientist, MCEER, State University of New York at Buffalo, USA*
Email: jwdai@iem.net.cn

ABSTRACT:
Studies of 3D temporal characteristics of earthquake ground motions and the structural responses are definitely motivated by seismic damage to structures. It is well known that six degree-of-freedom-correlated dynamic forces can cause complicated structural damage and the unidirectional based indexes may only capture the damage potential of a ground motion that can be observed in the projected direction. However, most of the currently used ground motion indices largely simplify the essential kinematics relationship of the 3D time histories; no longer contain sufficient information to differentiate the various causes and formations of the damage characteristics of the underlying ground motions. To understand the 3D temporal characteristics of the ground motion and their impact on structures, a different set of 3D temporal parameters can be used, including instantaneous tangential, normal accelerations and two temporal rotations. In this paper, using the recently developed 3D temporal characteristics analysis, the typical features of the seismic responses of a down scaled of a high rise building structure (1/30) in a shaking table test are analyzed and compared with that of the corresponding ground excitations. Some useful phenomena are found: The occurring time of the maximum $|a|$ and the peak values of $|a|$ is not only determined by the peak values of negative a_T, positive a_T and a_N but also by the negative a_T, positive a_T and a_N ,in most cases, the maximum a_N and $|a|$ usually happened simultaneously or very closely with each other, which indicates that the direction change plays an important role to the PGAs of not only the ground motions but also the seismic response of structures.

KEYWORDS:
3D temporal characteristics, Ground motion, Structural response, Shaking table test

1. INTRODUCTION

Ground motions with prominent pulses are more destructive of structures. General studies indicate that structural damage is closely connected with the large ground deformation and great energy carried by large velocity pulse of ground motions; however, not only destructive effect on structure is related to large velocity pulse and large deformation, but also large acceleration pulse and the acceleration differential pulse play an important part on structure damage. The theory of 3D temporal characteristics analysis could reflect the influence coursed by large velocity pulse, large acceleration pulse, acceleration differential pulse and so on.

The 3D temporal characteristics analysis, including the normal and tangential accelerations and temporal curvature and torsion, is a useful tool to help us look into the unique characteristics of earthquake ground motions even the structural responses. In particular, after taking away the kinematics relations among the acceleration, velocity and displacement time histories, we may find these temporal characteristics particularly helpful for identifying certain nonlinear dynamics involved in the ground motions. In this paper, we try to evaluate characteristics of structural seismic responses by using the 3D temporal characteristics analysis. The shaking table test results for a down scaled model of a high rise building is analyzed and compared.

2. SHAKING TABLE TEST FOR A DOWN SCALED HIGH RISE BUILDING

2.1 General information of the down scaled high rise building

The prototype structure is The World Trade Center of Shenzhen City, China. Similitude ratio in length is 0.029:1. The site classification is II; seismic fortification intensity is 7 in Chinese Building Code. The prototype structure is is a 54 stories building with height of 232m above the ground level, skirt building is 5 stories with height of 25m, and the basement is 4 stories.

The down scaled model is shown in Fig 1. It had experienced 2-directional earthquake simulation tests on the shaking table under ground excitations of 0.039g (0.026g), 0.109g (0.089g), and 0.183g (0.149g) etc. Initial fundamental frequency of the down scaled model is 3.68Hz. After series excitations, the fundamental frequency decreased to be of 2.32Hz. Results indicate that model structure has subjected to certain degree of damage.

Fig. 1 Scaled model

2.2 Ground motions

During the shaking table test, selected Chi-Chi earthquake ground motion records are used. The basic information of the ground motions is listed in table 1. 2-directional earthquake ground motions are used in shaking table test.

Table 1 The selected ground motion

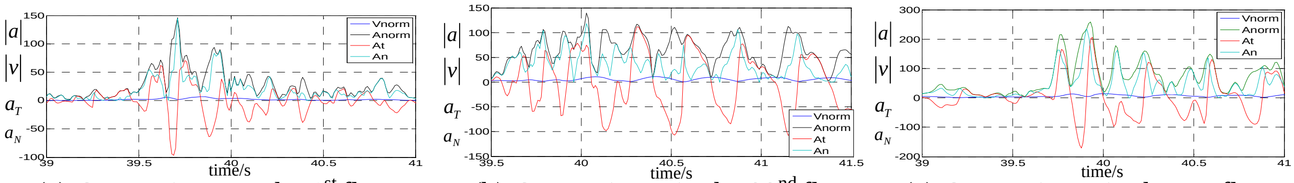
name	Station	Dist(Km)	UD(gal)	NS(gal)	EW(gal)	Latitude	Longitude
Quake1	TCU045	76.32	353	512	463	24.5417	120.9138
Quake2	TCU068	46.3	519	362	502	24.278	120.7657
Quake3	TCU076	13.7	275.4	420	340	23.9077	120.6757
Quake4	CHY080	31.7	715.9	841.5	792.4	23.5972	120.6777

3. 3D TEMPORAL CHARACTERISTICS ANALYSES

In shaking table test, the scale model of the high rise structure is excited by 2-directional earthquake ground motions from three different directions: 0 degree direction, 45 degree direction, and 90 degree direction. Sensors are placed at the 1st, 6-1st, 22nd, 38th, and top floor respectively. The absolute acceleration time history records from sensors placed at the 1st floor, 22nd floor, and top floor are analyzed and the absolute acceleration time histories are processed into absolute velocity time histories and absolute displacement time histories by integral. The 3D temporal characteristics analysis is used to look into the unique characteristics of the structural responses. Analysis results are as follows.

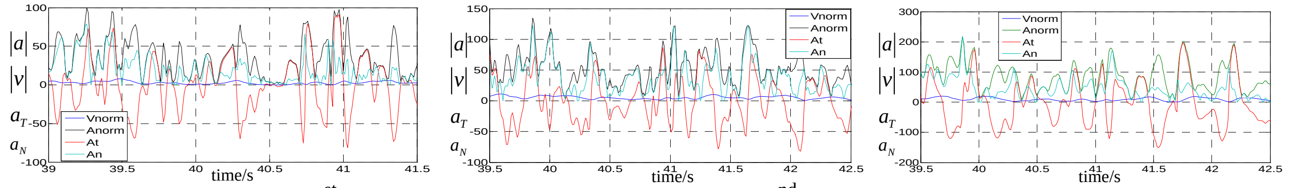
3.1 The Results of Quake1 Excitation

Comparisons of a_T , a_N , $|a|$, $|v|$ and $|d|$ are shown by Fig2-4 and table 2. From table 2, it is found that the time when the maximum $|a|$ occurred and the peak values of $|a|$ are not only determined by the peak values of negative a_T , positive a_T and a_N , but also by the time when the negative a_T , positive a_T and a_N occurred. What's more, in most cases, the maximum a_N and $|a|$ usually happened simultaneously or very closely with each other, which indicates that the change of direction plays an important role on PGAs. Fig 2-4 shows that the amplitudes of tangential accelerations are biased. When the scale model is excited by quake1 in 0 directions, the largest peak deceleration of the1st floor is 96.33 cm/s^2; whereas the largest peak acceleration of the 1st floor is 70.36 cm/s^2. According to Fig2-4 and table 2, the maximum $|a|$ and $|v|$ are kinematically unrelated, which suggest that the maximum $|a|$ is not caused by derivative of the maximum $|v|$; likewise, the maximum $|d|$ and $|a|$ are kinematically unrelated which suggest that the maximum $|v|$ is not caused by derivative of the maximum $|d|$.



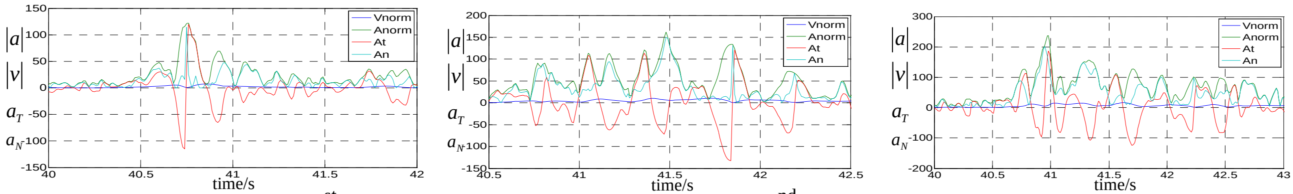
(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.2 when the scale model is excited by quake1 in 0 degree direction



(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.3 when the scale model is excited by quake1 in 45 degree direction



(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.4 when the scale model is excited by quake1 in 90 degree direction

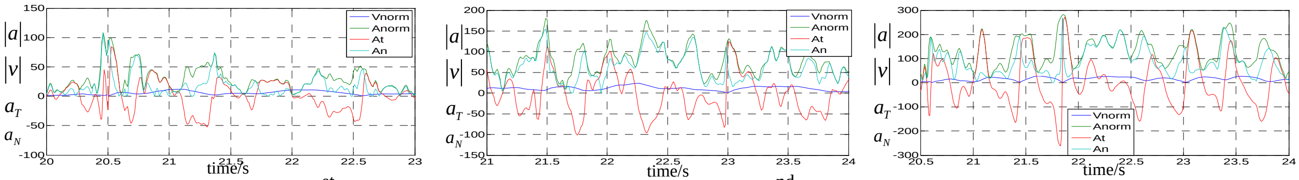
Table 2 The results excited by quake1

Floor	Items	In 0 degree direction		In 45 degree direction		In 90 degree direction	
		Time when peak occurs(s)	Peak value	Time when peak occurs(s)	Peak value	Time when peak occurs(s)	Peak value
The 1st floor	negative a_T	39.69	-96.33	41.03	-81.29	40.74	-114.89
	positive a_T	39.75	70.36	40.97	90.93	**40.76**	119.80
	a_N (cm/s^2)	**39.71**	144.85	**39.26**	78.99	40.75	114.65
	$\|a\|$ (cm/s^2)	**39.71**	145.72	**39.26**	99.90	**40.76**	122.42
	$\|v\|$ (cm/s)	39.85	6.82	39.48	7.80	40.87	7.36
	$\|d\|$ (cm)	44.75	0.83	41.57	1.36	40.76	0.82
The 22nd floor	negative a_T	41.15	-107.59	42.08	-82.02	41.84	-132.61
	positive a_T	40.31	111.81	40.94	86.45	41.86	121.61
	a_N (cm/s^2)	**40.03**	118.31	**39.86**	122.45	**41.48**	149.59
	$\|a\|$ (cm/s^2)	**40.03**	139.99	**39.86**	134.74	**41.48**	161.33
	$\|v\|$ (cm/s)	40.41	11.19	39.59	11.23	41.73	10.65
	$\|d\|$ (cm)	40.27	1.32	41.66	2.11	41.86	1.42
The top floor	negative a_T	39.88	-170.32	41.54	-150.45	41.70	-123.84
	positive a_T	39.94	206.46	41.75	196.67	40.98	186.12
	a_N (cm/s^2)	**39.91**	235.20	**39.86**	217.19	**40.95**	201.24

	$\lvert a \rvert$ (cm/s^2)	**39.93**	258.12	**39.86**	217.23	**40.98**	236.97
	$\lvert v \rvert$ (cm/s)	40.01	14.82	39.70	20.28	41.63	16.50
	$\lvert d \rvert$ (cm)	42.28	1.69	41.72	3.12	41.38	2.16

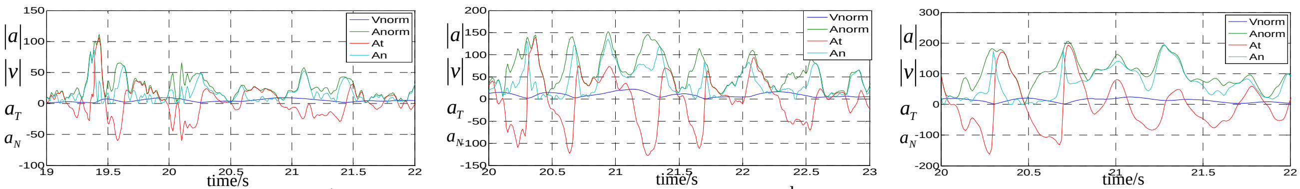
3.2 The Results of Quake2 Excitation

Comparisons of a_T, a_N, $\lvert a \rvert$, $\lvert v \rvert$ and $\lvert d \rvert$ are shown by Fig5-7 and in table 3. From table 3, it is also found that the time when the maximum $\lvert a \rvert$ occurred and the peak values of $\lvert a \rvert$ are not only determined by the peak values of negative a_T, positive a_T and a_N, but also by the time when the negative a_T, positive a_T and a_N occurred. What's more, in most cases, the maximum a_N and $\lvert a \rvert$ usually happened simultaneously or very closely with each other, which indicates that the change of direction plays an important role on PGAs. Fig 5-7 shows that the amplitudes of tangential accelerations are biased. When the scale model is excited by quake2 in 0 degree direction, the largest peak deceleration of the 1st floor is 52.72 cm/s^2; whereas the largest peak acceleration of the 1st floor is 84.34 cm/s^2. According to the Fig5-7 and table 3, the time when maximum $\lvert a \rvert$ occurred are almost all followed by the time when maximum $\lvert v \rvert$ occurred, which suggests that the maximum $\lvert v \rvert$ and $\lvert a \rvert$ are kinematically related; likewise, the time when maximum $\lvert v \rvert$ occurred are almost all followed by the time when maximum $\lvert d \rvert$ occurred, which indicates that the maximum $\lvert v \rvert$ and $\lvert d \rvert$ are kinematically related.



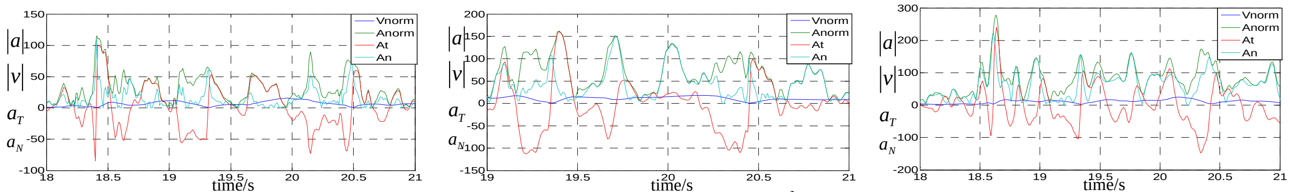
(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.5 when the scale model is excited by quake2 in 0 degree direction



(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.6 when the scale model is excited by quake2 in 45 degree direction



(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.7 when the scale model is excited by quake2 in 90 degree direction

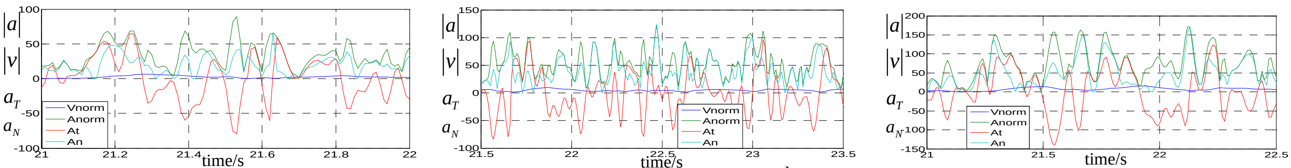
Table 3 The results excited by quake2

Floor	Items	In 0 degree direction		In 45 degree direction		In 90 degree direction	
		Time when peak occurs(s)	Peak value	Time when peak occurs(s)	Peak value	Time when peak occurs(s)	Peak value
The 1st floor	negative a_T	21.31	-52.72	19.58	-59.89	18.40	-84.87
	positive a_T	20.53	84.34	**19.43**	105.81	18.42	101.04
	a_N (cm/s^2)	**20.46**	107.45	19.39	85.74	**18.41**	108.55

	$\lvert a\rvert$ (cm/s^2)	**20.46**	108.10	**19.43**	111.71	**18.41**	115.12
	$\lvert v\rvert$ (cm/s)	21.11	11.92	20.91	9.47	19.96	15.39
	$\lvert d\rvert$ (cm)	22.59	3.95	21.46	3.21	20.49	5.30
The 22nd floor	negative a_T	21.75	-101.81	21.26	-127.07	19.22	-112.57
	positive a_T	23.01	124.48	20.37	138.91	**19.40**	160.61
	a_N (cm/s^2)	**21.49**	154.81	**20.94**	134.90	19.71	150.79
	$\lvert a\rvert$ (cm/s^2)	**21.49**	180.35	**20.94**	152.27	**19.40**	162.66
	$\lvert v\rvert$ (cm/s)	22.25	23.81	21.14	22.36	20.19	18.38
	$\lvert d\rvert$ (cm)	22.46	6.05	21.35	5.42	20.46	5.94
The top floor	negative a_T	21.83	-260.67	20.28	-162.44	21.70	-181.80
	positive a_T	**21.87**	270.88	**20.73**	193.87	18.64	240.89
	a_N (cm/s^2)	21.85	267.14	21.28	194.55	**21.73**	253.02
	$\lvert a\rvert$ (cm/s^2)	**21.86**	282.60	**20.73**	206.73	**18.63**	276.94
	$\lvert v\rvert$ (cm/s)	21.62	28.16	21.09	24.36	20.15	24.98
	$\lvert d\rvert$ (cm)	21.45	6.37	21.30	5.23	20.42	7.10

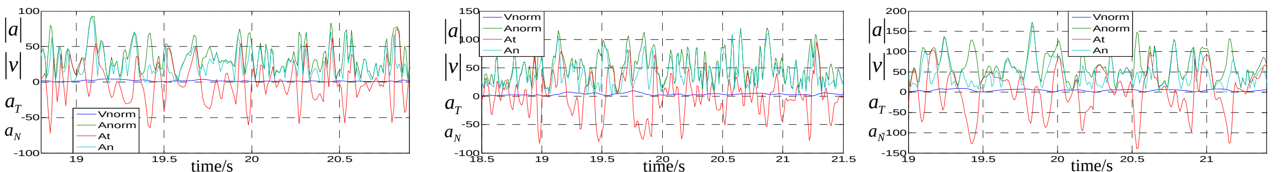
3.3 The Results of Quake3 Excitation

Comparisons of a_T , a_N , $\lvert a\rvert$, $\lvert v\rvert$ and $\lvert d\rvert$ are shown by Fig8-10 and in table 4. From table 4, it is found that the time when the maximum $\lvert a\rvert$ occurred and the peak values of $\lvert a\rvert$ are not only determined by the peak values of negative a_T , positive a_T and a_N , but also by the time when the negative a_T , positive a_T and a_N occurred. What's more, in most cases, the maximum a_N and $\lvert a\rvert$ usually happened simultaneously or very closely with each other, which indicates that the change of direction plays an important role on PGAs. Fig 8-10 shows that the amplitudes of tangential accelerations are biased. When the scale model is excited by quake3 in 0 degree direction, the largest peak deceleration of the 1st floor is 79.39 cm/s^2; whereas the largest peak acceleration of the 1st floor is 64.89cm/s^2. According to the Fig8-10 and table 4, the maximum $\lvert a\rvert$ and $\lvert v\rvert$ are kinematically unrelated, which suggests that the maximum $\lvert a\rvert$ is not caused by derivative of the maximum $\lvert v\rvert$; however, the time when maximum $\lvert d\rvert$ occurred almost all precedes the time when maximum $\lvert v\rvert$ occurred, which indicates that the maximum $\lvert v\rvert$ and $\lvert d\rvert$ are kinematically related.



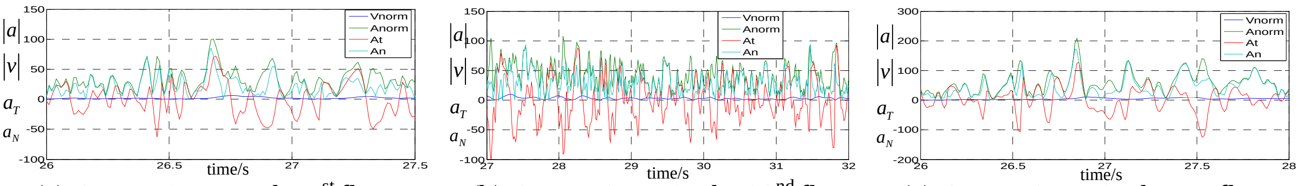
(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.8 when the scale model is excited by quake3 in 0 degree direction



(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.9 when the scale model is excited by quake3 in 45 degree direction



(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

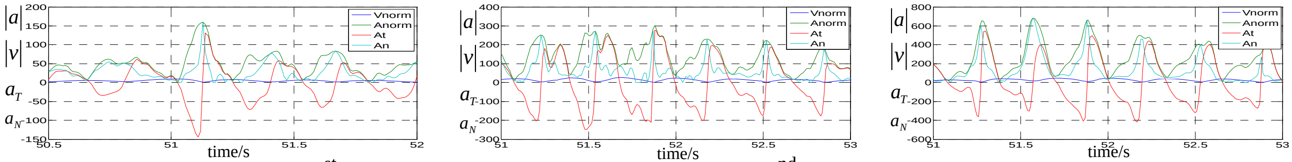
Fig.10 when the scale model is excited by quake3 in 90 degree direction

Table 4 The results excited by quake3

Floor	Items	In 0 degree direction		In 45 degree direction		In 90 degree direction	
		Time when peak occurs(s)	Peak value	Time when peak occurs(s)	Peak value	Time when peak occurs(s)	Peak value
The 1st floor	negative a_T	**21.53**	-79.39	18.85	-71.79	26.45	-61.89
	positive a_T	21.24	64.89	20.83	75.80	26.69	72.00
	a_N (cm/s^2)	22.65	66.37	**19.09**	91.96	**26.67**	85.01
	$\|a\|$ (cm/s^2)	**21.53**	89.32	**19.09**	93.04	**26.68**	100.34
	$\|v\|$ (cm/s)	21.29	6.80	19.19	4.51	26.76	6.27
	$\|d\|$ (cm)	21.64	1.03	12.33	1.39	19.91	1.72
The 22nd floor	negative a_T	21.57	-83.58	18.98	-82.55	**27.06**	-99.37
	positive a_T	23.06	95.75	21.28	94.71	31.83	91.83
	a_N (cm/s^2)	**22.47**	123.25	**20.65**	118.46	27.54	92.19
	$\|a\|$ (cm/s^2)	**22.47**	123.38	**20.87**	120.33	**28.06**	107.75
	$\|v\|$ (cm/s)	21.87	9.80	19.76	9.70	27.34	9.81
	$\|d\|$ (cm)	21.67	1.69	12.41	1.88	19.92	2.21
The top floor	negative a_T	21.55	-139.63	20.53	-139.14	27.53	-123.75
	positive a_T	22.23	124.32	19.17	104.51	26.86	127.33
	a_N (cm/s^2)	**22.13**	170.47	**19.83**	163.18	**26.84**	172.87
	$\|a\|$ (cm/s^2)	**22.12**	171.69	**19.83**	172.42	**26.85**	208.76
	$\|v\|$ (cm/s)	21.93	15.79	19.36	9.73	26.91	10.94
	$\|d\|$ (cm)	21.68	2.44	12.42	1.48	19.91	1.99

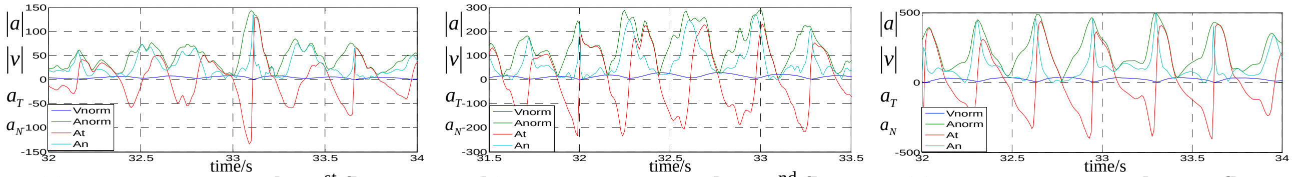
3.4 The Results of Quake4 Excitation

Comparisons of a_T, a_N, $|a|$, $|v|$ and $|d|$ are shown by Fig11-13 and in table 4. From table 5, it is found that the time when the maximum $|a|$ occurred and the peak values of $|a|$ are not only determined by the peak values of negative a_T, positive a_T and a_N, but also by the time when the negative a_T, positive a_T and a_N occurred. What's more, in most cases, the maximum a_N and $|a|$ usually happened simultaneously or very closely with each other, which indicates that the change of direction plays an important role on PGAs. Fig 11-13 shows that the amplitudes of tangential accelerations are biased. When the scale model is excited by quake4 in 0 degree direction, the largest peak deceleration of the 1st floor is 144.10 cm/s^2; whereas the largest peak acceleration of the 1st floor is 131.14 cm/s^2. According to Fig11-13 and table 4, the maximum $|a|$ and $|v|$ are kinematically unrelated, which suggests that the maximum $|a|$ is not caused by derivative of the maximum $|v|$; likewise, the maximum $|d|$ and $|v|$ are kinematically unrelated which indicates that the maximum $|v|$ is not caused by derivative of the maximum $|d|$.



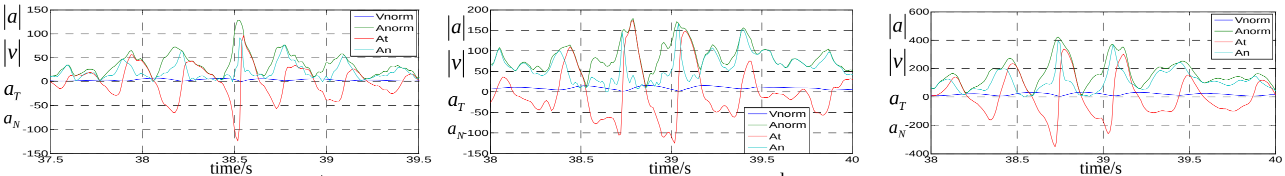
(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.11 when the scale model is excited by quake4 in 0 degree direction



(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.12 when the scale model is excited by quake4 in 45 degree direction



(a) Comparisons at the 1st floor (b) Comparisons in the 22nd floor (c) Comparisons in the top floor

Fig.13 when the scale model is excited by quake4 in 90 degree direction

Table 5 The results excited by quake4

Floor	Items	In 0 degree direction		In 45 degree direction		In 90 degree direction	
		Time when peak occurs(s)	Peak value	Time when peak occurs(s)	Peak value	Time when peak occurs(s)	Peak value
The 1st floor	negative a_T	51.11	-144.10	33.09	-133.61	**38.52**	-123.72
	positive a_T	51.14	131.14	33.13	130.11	38.55	96.50
	a_N (cm/s^2)	**51.13**	159.06	**33.11**	134.89	38.53	91.45
	$\|a\|$ (cm/s^2)	**51.13**	160.41	**33.10**	143.49	**38.52**	128.51
	$\|v\|$ (cm/s)	51.04	9.44	33.01	8.31	38.08	7.46
	$\|d\|$ (cm)	51.14	1.15	32.56	1.09	38.22	1.08
The 22nd floor	negative a_T	51.49	-247.98	32.24	-233.80	39.02	-124.84
	positive a_T	**51.88**	278.11	33.01	233.32	**38.79**	174.35
	a_N (cm/s^2)	51.87	273.96	**32.97**	268.03	39.04	165.36
	$\|a\|$ (cm/s^2)	**51.88**	302.15	**33.00**	292.76	**38.79**	178.92
	$\|v\|$ (cm/s)	51.69	27.13	32.45	29.80	38.87	15.64
	$\|d\|$ (cm)	51.88	2.77	32.63	3.70	39.43	2.07
The top floor	negative a_T	52.17	-419.82	33.61	-403.69	38.72	-349.31
	positive a_T	51.30	546.55	32.66	439.81	38.77	337.97
	a_N (cm/s^2)	**51.57**	677.02	**33.30**	498.46	**38.74**	395.86
	$\|a\|$ (cm/s^2)	**51.58**	680.80	**33.30**	499.12	**38.74**	421.08

	$\lvert v \rvert$ (cm/s)	52.02	46.53	32.79	39.95	38.88	32.88
	$\lvert d \rvert$ (cm)	51.89	5.11	32.64	4.47	39.44	3.97

4. CONCLUSIONS

This paper summarizes a study of some 3D characteristics of seismic response of the scale model for high-rise structure. Through examining the seismic response histories of the scale model excited by four different ground motions in three different directions respectively, we could make conclusions as follows:

1. The 3D characteristics differ from the traditional ones produced by dynamic or static bending and torsion. This paper analyses some 3D characteristics such as instantaneous tangential acceleration a_T, instantaneous normal acceleration a_N, Euclidean norm of acceleration vector $\lvert a \rvert$, Euclidean norm of velocity vector $\lvert v \rvert$, and Euclidean norm of displacement vector $\lvert d \rvert$. When the scale model for high-rise structure is excited by the four different ground motions in three different directions, the 3D characteristics of structural response vary from one another, which suggest the unique dynamic process of the structural response.
2. It is found that the time when maximum $\lvert a \rvert$ occurred and the peak values of $\lvert a \rvert$ are not only determined by the peak values of negative a_T, positive a_T and a_N but also by the time when the negative a_T, positive a_T and a_N occurred. What's more, in most cases, the maximum a_N and $\lvert a \rvert$ usually happened simultaneously or very closely with each other, which indicates that the change of direction plays important role to PGAs.
3. The maximum $\lvert a \rvert$ and $\lvert v \rvert$ are mostly kinematically unrelated, which suggests that the maximum $\lvert a \rvert$ is not caused by derivative of the maximum $\lvert v \rvert$; likewise, the maximum $\lvert d \rvert$ and $\lvert v \rvert$ are mostly kinematically unrelated which also indicates that the maximum $\lvert v \rvert$ is not caused by derivative of the maximum $\lvert d \rvert$.The relation between maximum $\lvert a \rvert$ and maximum $\lvert v \rvert$ depends on the accumulative effect of acceleration and deceleration.
4. Fig 2-37 and table 2-5 show that the amplitudes of tangential accelerations are biased to different sides, which may be connected with the characteristics of structural response and the excitations of ground motions.

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NOTATION

The following symbols are used in this paper:

a_T (cm/s^2) = instantaneous tangential acceleration;
a_N (cm/s^2) = instantaneous normal acceleration;
$\lvert a \rvert$ (cm/s^2) = Euclidean norm of acceleration vector;
$\lvert v \rvert$ (cm/s) = Euclidean norm of velocity vector;
$\lvert d \rvert$ (cm)= Euclidean norm of displacement vector.

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