Study of the seismic damage regularity of ancient masonry pagodas in the 2008 Wenchuan Earthquake

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Abstract

This paper investigates the characteristics and regularity of damage to ancient masonry pagodas in Sichuan province in high seismic intensity areas during the Wenchuan Earthquake by a statistic analyses method. Emphasizing the seismic damage of foundation and structural components of pagodas, the relation between seismic intensity and damage degree of pagodas is discussed. The analyses results indicated that masonry pagodas are hypersensitive to seismic action; the damage condition of pagodas are aggravated with the increase of seismic intensity, and the structural type, conformation character and site condition have a obvious influence on the degree of seismic damage of pagodas. Aiming at the three main damage characteristics, ground distortion, weak construction crack, and structural collapse, the typical cases are selected to demonstrate the regularity of seismic damage to ancient pagodas.
Keywords: ancient masonry pagoda, seismic intensity, site condition, construction characteristics, damage regularity.

1   Introduction

The ancient pagoda is a precious architectural heritage and with an important historical and art value. In the Wenchuan Earthquake of magnitude 8.0 on May 12th, 2008, a lot of pagodas in the high intensity regions of Sichuan province in China were severe damaged or collapsed, which aroused the extraordinary attention of the administrative departments and scholar community [1–4]. Based on the investigated data on pagodas in the Sichuan province, this paper analyzed the damage regularity of ancient pagodas in seismic intensity areas of VI degree

to X degree during the Wenchuan Earthquake, discussed the influence of the ground condition, conformation character and structural type to damage degree of pagodas. Furthermore, aiming at the three main damage characteristics, ground distortion, weak conformation crack and structural collapse, the typical cases are selected to demonstrate seismic damage regularity of ancient pagodas.

2 Basic information and definition on seismic damage of ancient pagodas

There were a total of 61 pagodas in seismic intensity areas of VI to X degree during the Wenchuan Earthquake. The basic information of the pagodas is listed in Table 1, and Figure 1 shows the locations of the pagodas according to their serial number.
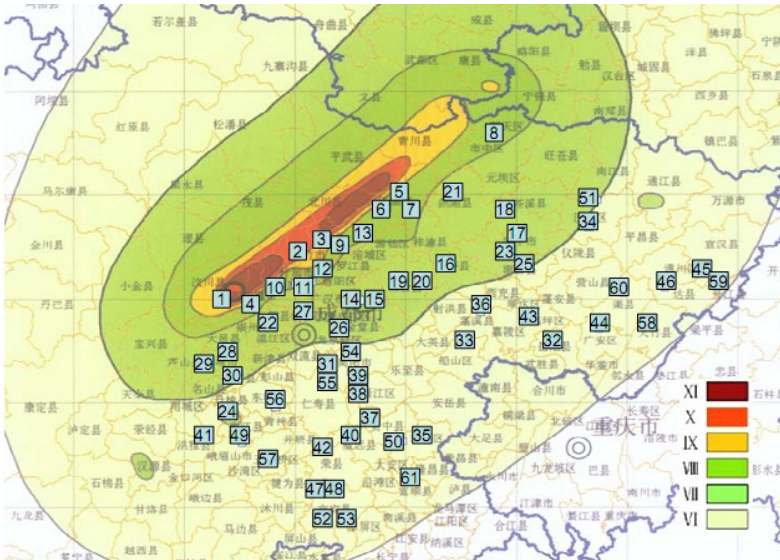

Figure 1:   Intensity distribution and locations of pagodas in Sichuan province.

The classification information of pagodas is as follows: (1) Classification according to structural type: 34 pagodas belong to the multi-storey-pavilion-style, 25 pagodas belong to the dense-Eaves-style, and 2 pagodas belong to the Vase-style. (2) Classification according to building material: 58 brick pagodas, 2 stone pagodas, and 1 adobe pagoda. (3) Classification according to construction field: 16 pagodas were built on flat ground, 5 pagodas were built on a riverside, 31 pagodas were built on a mountaintop, and 9 pagodas were built on a hillside.

To classify the seismic damage of pagodas reasonably, aiming at the repair demand of cultural heritage and the damage character of components of pagodas, the definition on grade and character of seismic damage of ancient pagodas is proposed (see Table 2).

Table 1:   Basic information of pagodas.

Seismic intensity area	No.	Name of pagoda	City or county	D.G.	No.	Name of pagoda	City or county	D.G.
≥X	1	Jionglan	Wenchuan	5	2	Wenfeng	Mianzhu	5
IX	3	Wenxing	Anxian	5	4	Kuiguang	Dujiangyan	4
VIII	5	Nanyan	Jiangyou	5	6	Yunlong	Jiangyou	4
	7	Nansan	Mianyang	4	8	Laiyan	Guangyuan	4
	9	Longhu	Deyang	4	10	Zhengjuesi	Pengzhou	4
	11	Yunjuyuan	Pengzhou	4	12	Zhenguosi	Pengzhou	3
	13	Beita	Zhongjiang	4	14	Nanta	Zhongjiang	3
	15	Feiying	Jiangyou	3				
VII	16	Bita	Yantin	4	17	Baita	Langzhong	4
	18	Chongxia	Cangxi	4	19	Beita	Santai	4
	20	Donta	Santai	4	21	Beita	Jiange	4
	22	Zikuta	Chongzhou	3	23	Shita	Langzhou	3
	24	Baita	Danlun	3	25	Shenba	Nanbu	3
	26	Ruiguang	Jintang	3	27	Baoguangsi	Xindu	3
	28	Huilan	Qionlai	2	29	Shitasi	Qionlai	2
	30	Fenweng	Pujiang	2				
VI	31	Shengdesi	Jianyang	3	32	Baita	Yuechi	3
	33	Shanji	Suining	3	34	Lingyuan	Bazhong	3
	35	Sanyuan	Neijiang	3	36	Jiufengsi	Pengxi	2
	37	Cangjie	Zizhong	2	38	Sanyuan	Zizhong	2
	39	Baita	Ziyang	2	40	Baita	Weiyuan	2
	41	Xiuwen	Hongya	2	42	Zhennan	Rounxian	2
	43	Wuliang	Nanchong	2	44	Baita	Guangan	2
	45	Baoquan	Kaijiang	2	46	Longzhua	Dazhou	2
	47	Baita	Yibin	2	48	Heita	Yibin	2
	49	Lingbao	Leshan	2	50	Gaosi	Neijiang	2
	51	Buyue	Bazhong	2	52	Jiuzhou	Yibin	1
	53	Dengying	Junlian	1	54	Hongbai	Jianyang	1
	55	Timing	Jianyang	1	56	Dawansi	Meishan	1
	57	Baita	Sanjiang	1	58	Wenfeng	Dazhu	1
	59	Wenbi	Kaijiang	1	60	Wenfeng	Quxian	1
	61	Jionglan	Fushun	1				

Note: No. – Serial number of pagoda, DG – Damage grade of pagoda (see table 2).

Table 2: Definition on grade and character of seismic damage of ancient pagodas.

Damage grade	Damage degree	Damage character of components of pagoda	Repair demand after earthquake
1	Slight damage	Tiny cracks on tower body, or slight damage on eaves or steeple	Minor repair
2	Local damage	Visible cracks on tower body, or local break on eaves or steeple	Local repair
3	Middling damage	Obvious cracks on tower body, or tower body light lean, or steeple collapse	Major restoration
4	Severe destruction	Through cracks on tower body, or tower body obvious lean, or partial storey collapse	Whole restoration
5	Whole destruction	Entire collapse of tower body	Reconstruction

3 The relation between seismic intensity and damage degree of pagodas

According to the definition of Table 2, the 61 pagodas are classified in five damaged conditions. The seismic intensity of every pagoda location is confirmed based on the "Seismic intensity distribution of the M_s 8.0 Wenchuan Earthquake". [5] The classification ratio of pagodas is list in Table 3.

Table 3: Classification ratio of seismic damage of pagodas in Sichuan province.

Seismic intensity area	HPGA (m/s²) [6]	N. of pagodas in the area	Damage degree									
			Slight damage		Local damage		Middling damage		Severe destruction		Whole destruction	
			N.	ratio	N.	ratio	N.	ratio	N.	ratio	N.	ratio
VI	0.45—0.89	31	10	32%	16	52%	5	16%				
VII	0.90—1.77	15			3	20%	6	40%	6	40%		
VIII	1.78—3.53	11					3	27%	7	64%	1	9%
IX	3.54—7.07	2							1	50%	1	50%
≥X	7.08—14.14	2									2	100%
Total number and ratio of pagodas		61	10	16%	19	31%	14	23%	14	23%	4	7%

Note: HPGA – horizontal peak ground acceleration.

From Table 3 we can find that the seismic damage degree of pagodas with increasing of seismic intensity tends to be serious, and there is a clear corresponding relation between the two. Be careful, the pagoda is very sensitive to earthquake action; there is a certain number of pagodas suffered middling damage in the seismic intensity area of VI degree.

4 Regularity of seismic damage of pagodas due to ground distortion

4.1 Statistical analysis of ground distortion damage of pagodas

The masonry pagoda has a heavy deadweight, larger slenderness ratio and a relatively small foundation, which is sensitive to ground distortion caused by earthquakes. About 11 pagodas suffered seismic damage of ground distortion in the Wenchuan Earthquake, such as uneven subsidence of foundation or lean of tower body. Table 4 lists the construction site and slenderness ratio (H/D) of these pagodas, and classifies the damage of pagodas to the three conditions based on the degree of foundation subsidence or tower body lean.

Table 4:   Classification of seismic damage of pagodas due to ground distortion.

Seismic intensity area	Construction site	Seismic damage condition of foundation or body of pagoda					
		Foundation subsidence, tower body crack		Foundation subsidence, tower body lean		Foundation serious subsidence, tower body serious lean	
		No. of pagoda	H/D	No. of pagoda	H/D	No. of pagoda	H/D
VI	riverside	44	4.3				
	mountaintop	40 38	3.1 4.5	32 45 44	3.4 4.1 4.1	35	3.8
VII	riverside			28	4.3	25	4.7
	mountaintop					26	4.8
VIII	hillside					11	4.0

Note: H – highness of pagoda; D – subtense length of bottom of pagoda.

We can see from table 4: (1) The construction site conditions have an obvious influence on the seismic damage of ground distortion: a) The pagodas built on flat ground, no damage due to ground distortion; b) There are a total of 5 pagodas built on the riverside, and 3 pagodas with ground distortion, accounted for 60% of the total; c) There are a total 40 pagodas built on a mountaintop or hillside, and 8 pagodas with damage of ground distortion, accounted for 20% of the total. (2) The damage degree of ground distortion and slenderness ratio H/D of pagoda has some relevance; the slenderness ratio of all the 11 damaged pagodas is greater than 3.0, so it is easy to aggravate the inclined degree of the pagoda in the uneven settlement condition of foundations. (3) The damage degree of ground distortion increases with increasing seismic intensity, and has led to serious deformation of the upper structure. Note, that there are 3 pagodas with serious damage due to the failure of foundation in the seismic intensity area of VI and VII degrees.

4.2 Typical pagodas with a serious lean due to ground distortion

4.2.1 Shenba pagoda in Nanbu County

Shenba pagoda is a 7-storey hexagonal multi-storey-pavilion brick tower, 14 meters high. The pagoda is located in the inundated area of a lake for a flood reservoir, and the foundation is damaged by a change in water level. During the Wenchuan Earthquake, the foundation of the pagoda was subsidence, and led to a serious tilt of the tower body (Fig. 2).

4.2.2 Sanyuan pagoda in Neijiang City

Sanyuan Pagoda is a 10-storey octagonal multi-storey -pavilion brick tower, 62.7 meters high. The pagoda is located on the top of San-yuan Mountain, shrubs and weeds growing into the brick joints resulted in cracking and an incline of the foundation. The seismic action of the Wenchuan Earthquake aggravated the inclined condition of San-yuan pagoda. According to the measure of global positioning system, the top displacement value is 0.631 meters and the deviation angle is 14°41′50″, so this pagoda has been identified as a dangerous tower (Fig. 3).

Figure 2:   Shenba   Figure 3:   Sanyuan   Figure 4:   Yunjuyuan
             pagoda.   pagoda.   pagoda.

4.2.3 Yunjuyuan pagoda in Penzhou City

Yunjuyuan pagoda is a 13-storey square Dense-eaves brick tower, 20.9 meters high. The pagoda is located on the hillside of a mountain and the foundation had been damaged by long-term soil and water loss before the Wenchuan Earthquake. The Wenchuan Earthquake led to the serious displacement of the foundation, and the tower body tilted about 10 cm; obvious cracks appeared (Fig. 4).

5   Regularity of seismic damage of pagodas due to weak conformation

5.1 Statistical analysis of weak conformation damage of pagodas

Because of the low tensile strength of masonry, the weak part of the tower body easily cracks under the tension resulting from an earthquake. For the pagoda with a string of door holes set up in the same position of each storey, the wall between the upper and lower holes is a weak part and it is easy to produce shear deformation leading to vertical splitting of the wall under earthquake action.

In the Wenchuan Earthquake, about 20 pagodas belong to the damage type of masonry wall cracking. Among them, 8 pagodas suffered a masonry split along the vertical opening walls. These pagodas with split damage are list in table 5. The cracking conditions of wall are classified into three types, and the vertical opening state of the wall is also listed as a reference.

Table 5 shows: (1) the cracking degree of the tower body increases with the increase of seismic intensity. (2) The door holes along the vertical tower body form a weak conformation, and the wall with a string of door holes is the main reason for a through split of the tower body.

Table 5:   Classification of seismic damage due to weak conformation.

Seismic intensity area	Construction site	Cracking conditions of the wall					
		Local cracking		Serious cracking		Through split	
		No. of pagoda	Opening state	No. of pagoda	Opening state	No. of pagoda	Opening state
VI	flat ground	31	A				
	mountaintop			34	A		
VII	flat ground			27 24	C B		
VIII	mountaintop			12	A	10 9	A A
IX	flat ground					4	A

Note: The vertical opening state of the wall : A – door hole set on every storey; B – door hole and blind hole set on the storey alternately; C – blind hole set on every storey.

5.2 The typical pagodas with vertical split due to weak conformation

5.2.1 Kuiguang pagoda in Dujiangyan City

Kuiguang pagoda is a 17-storey hexagonal multi-storey-pavilion brick tower, 52.7 meters high. The door holes are set up in the same position of each storey (Fig. 5). During the Wenchuan Earthquake, the wall cracked thoroughly from the fifth storey to the top on the southwest and northeast sides of the tower body, the maximum crack width is 15 cm.

5.2.2 Lonhu pagoda in Deyang City

Lonhu pagoda is a 13-storey square dense-eaves brick tower, 37.8 meters high. During the Wenchuan Earthquake, on the north and south sides of the tower body the through cracks appeared from the bottom to the top along the vertical midline of the wall. The cracks split the tower body into two parts, leading to the destruction of the structure (Fig. 6).

5.2.3 Zhengjuesi pagoda in Pengzhou City

Zhengjuesi pagoda is a 13-storey square dense-eaves brick tower, 27.54 meters high. Under the seismic action of the Wenchuan Earthquake, visible cracks appeared on the four sides of tower body. On the west side of the tower body, a through crack of about 5 cm in width appeared along the vertical midline extending from the upside of the arch to the top of the tower (Fig. 7).
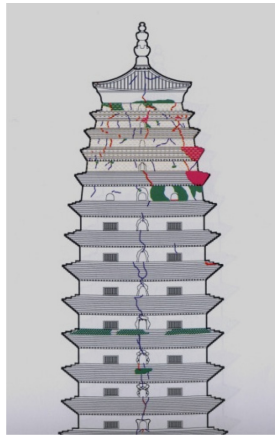

Figure 5: Kuiguang pagoda. Figure 6: Lonhu pagoda. Figure 7: Zhengjuesi pagoda.

6 Regularity of seismic damage of pagodas due to insufficient structural stiffness

6.1 Statistical analysis of structural failure of pagodas

The pagodas in the earthquake disaster area in the Sichuan province can be classified into two main structural types; the multi-storey-pavilion pagoda and the dense-eaves pagoda. In general, the dense-eaves pagoda cannot climb inside, because the inner space is filled with brick and rammed clay. The multi-storey-pavilion pagoda usually can climb to the top, it with a big inner space, so the structural stiffness is smaller than that of the dense-eaves pagoda. For the pagoda with a larger slenderness ratio H/D and smaller structural stiffness, under the strong earthquake action, the tower body is easy to form large lateral displacement and cause break or collapse.

There are a total of 14 pagodas which collapsed, partly or completely, in the Wenchuan Earthquake. Table 6 lists the names and construction sites of the pagodas, including their slenderness ratio H/D and structural type as a reference.

Table 6 shows: (1) Pagodas with structural failure where the slenderness ratio H/D is more than 3, the greater the slenderness ratio, the more serious the collapse. (2) From the point of view of structural type, the damage degree of the multi-storey-pavilion pagoda is serious; it is more obvious in the seismic intensity VII and VIII areas. The reason for this is the wall of the pavilion-style pagoda is relatively thin and the spatial stiffness is relatively small. (3) The collapse degree of the tower body increases with the increase of seismic intensity, and the mountain height has a significant amplifying effect on the action of the earthquake; in the seismic intensity VII and VIII areas, pagodas built on a mountaintop had a higher collapse ratio. Notable is, 7 pagodas suffered partial collapse in the seismic intensity area of VII degree, which indicates that the earthquake effects serious damage on pagodas.

Table 6:   Classification of seismic damage due to insufficient structural stiffness.

Seismic intensity area	Construction site	Damage condition of tower body						
		Collapse partly				Collapse completely		
		No. of pagoda	Collapsed storeys / total storeys	H/D	Structural type	No. of pagoda	H/D	Structural type
VII	flat ground	16	5/7	3.5	A			
	mountaintop	18 19 20 21 17	3/9 4/9 4/9 4/7 7/13	4.4 3.0 3.5 3.7 3.9	A A A A A			
VIII	mountaintop	13 7 6 8	3/13 4/9 7/9 7/13	3.0 3.1 3.1 5.3	B A A A	5	2.8	C
IX	flat ground					3	3.1	A
≥X	flat ground					2	5.5	B
	riverside					1	4.7	B

Note: Structural type of pagoda: A – multi-storey-pavilion style; B – dense-eaves style; C-vase style.

6.2 Typical pagodas with serious collapse due to insufficient structural stiffness

6.2.1 Bita pagoda in Yantin County

Bita pagoda is a 7-storey hexagonal multi-storey-pavilion brick tower, 31 meters high. The pagoda is located in a seismic intensity area of VII degree and the

construction site is flat ground. However, the upper five storeys have collapsed, with only the 9-meter high bottom storey remaining (Fig. 8). Testing after the Wenchuan Earthquake shows that the material strength of the pagoda is low and the masonry quality is poor. The niches weakened the structural stiffness of the thin wall, leading to the deficiency in seismic performance of the overall structure.

Figure 8:   Bita pagoda (left: before the earthquake; right: after the earthquake).

Figure 9:   Laiyan pagoda (left: before the earthquake; right: after the earthquake).

6.2.2 Laiyan pagoda in Guangyuan City

Laiyan pagoda is a 13-storey octagonal multi-storey-pavilion brick tower, 36 meters high. When the Wenchuan Earthquake took place on May 12th, 2008, the

8th storey to the top of the tower body collapsed at once. After that, a lot of aftershocks took place on May 25th to 27th in Qingchuan County and Ningqiang County, which led to the Laiyan pagoda being damaged again and the 6th and 7th storeys also collapsed (Fig. 9). Analysis shows that, Laiyan pagoda, being built on a mountaintop, its slenderness ratio H/D of 5.3, the amplifying effect of the mountain height on the action of the earthquake as well as the large slenderness ratio of the tower, are the important factors of pagoda collapse.

6.2.3 Wenxing pagoda in Anxian County

Wenxing pagoda is a 13-storey square multi-storey-pavilion adobe brick tower, 28 meters high; the first storey with a lower stone base and the remaining 12 storeys built from adobe brick. Its unique architectural materials and construction pattern are no longer seen in existing pagodas. The adobe brick is made from hemp, grass fibre and clay, with the mortar using sand, clay and a glutinous rice paste mixture, so the structural integrity of masonry tower is not high. Following up to IX degree seismic intensity in the region, the strong earthquakes led to this adobe tower collapsing entirely, with only the bottom, about 6 meters high, remaining (Fig. 10).

Figure 10:   Wenxing pagoda: (left: before the earthquake; right: after the earthquake).

7   Conclusion and suggestion

The damaged pagodas in the Wenchuan Earthquake are an important resource on the research of ancient architecture protection. Based on the data collection and field investigation, this paper discussed the damage regularity of ancient masonry pagodas, analyzed the relationship between the seismic intensity and damage degree of pagodas. Research shows that: (1) the damage degree of pagodas with the increasing of the seismic intensity tends to be serious; both

have a clear corresponding relationship. (2) The pagoda is very sensitive to the construction site condition; for the pagoda built on the riverside or mountaintop, the prevention of foundation seismic damage needs to be strengthened. (3) The structural type and conformation characteristics of the pagoda have a great influence on the damage degree; for the pagoda with a string of door holes set at the same position of each storey, attention needs to be paid to the identification of splitting resistance of the tower body; in addition, for the multi-storey-pavilion pagoda where the slenderness ratio H/D is larger than 3, and which is located in an area of seismic intensity equal or greater than VII degrees, attention needs to be paid to the evaluation of structural collapse resistance.

Acknowledgements

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