The application of SMA dampers in passive control of ancient tower structures

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ABSTRACT:

The majorities of Chinese present ancient pagodas all mix together the highlighted arts of foreign cultures and traditional architectures of China, and are typical masterpieces of ancient buildings. The ancient pagoda protecting research is a major task of cultural relic protection. In this paper the historical changes and engineering situations have be fully investigated and the material constituents, detailing types, existing inclination and cracks etc. are studied. Then, the mechanical properties of SMA wire are tested, and a desirable SMA damper is designed. The shaking table test had been executed on the ancient pagoda model structure with and without SMA dampers. Experimental results show that the model structures with SMA dampers can improve its earthquake resistance capacity so that the concluding remarks could not only provide a theoretical foundational and technical support, but provide references for protection and repair of other historical buildings.

KEYWORDS: ancient tower, passive control, SMA damper, table test

1 Introduction

China is a country with an ancient civilization and its architecture history has lasted for seven thousand years in particular, which left a large number of historic relics in China today. For example the ancient pagoda, as one part of the Chinese culture, plays a very important role in the development of the Chinese architecture. It is not only precious in historic value, but also in scientific research. According to statistics, at present, there are more than 3,000 ancient pagodas in China, thus China is also known as one of the countries which have the world's largest number of ancient pagodas with various styles and historic values.

Most of the existing ancient pagodas in China have experienced long-term development and the test of history, but also have experienced some changes of natural environment and the damage of natural disasters, so they have been said to be certain seismic capacities. However, most ancient pagoda, because of disrepair, coupled with the weakness of initial construction and internal hidden dangers and wind and rain erosion for many years, resulting in its current weak seismic capacity, so it is difficult to sustain or re-withstand earthquake, strong winds or other natural disasters. The Small Wild Goose Pagoda in Xi'an, Shaanxi province, the Flower Pagoda in Chezhou Mountain in Hebei province and Twin Pagodas in Shanxi province, have been damaged seriously in the earthquake. The famous Pagoda of FaMen Temple in Shaanxi province, in particular split after the earthquake and collapsed, which has ultimately brought great loss.

Therefore, it is worthwhile to make further research about how to improve ancient pagodas capacity to resist natural disasters while abiding by the principle in which its protection comes first and it must be restore the old to the original. Meanwhile, its completeness and reliability have been assured with its historic, artistic and scientific value preserved. In this paper, the author makes use of the special characteristics of the Shape Memory Alloy, (abbreviated as SMA) and develops a SMA damper applicable to a real seismic protection of the ancient pagoda and applies it to Seismic Protection Project of the ancient pagoda structure, which has effectively improved the seismic capacity of the ancient pagoda.

2 Investigation on a certain ancient pagoda

2.1 Historic value of the ancient pagoda

The ancient pagoda was built in the first year of Zhenguan, Tang Danasty, by early Arab missionaries of Abby • Wangesu. That is, in the year 627, more than 1,300 years ago. It is quite characteristic of Arabian architecture with great value. The pagoda is a living witness to the ancient silk route on the sea, playing an important role in the cultural contacts between the West and the East.

In 1990, sponsored by the UNASCO, famous archaeologists from different countries made an exploration along the Ancient Silk Route on the sea to China. They made the conclusion that China should well preserve the ancient pagoda, relics of historical interest in the world history. In 1996, the ancient pagoda was declared a top-priority national historic monument by the State Council. It fully demonstrates that china has put priority to the protection of the historic treasure.

2.2 Architectural features of the ancient pagoda

The pagoda made up of main pagoda and a small one takes the shape of conical (as shown in Fig.1). The main pagoda looks like a circular platform, which is made up of outer wall and inner wall. The diameter of outer wall on the bottom of the pagoda is 8.53m (calculated from the elevation of ±0.00m)，the diameter of outer wall on the top of the pagoda is 5.06m（calculated from the elevation of +23.25m)，the distance between the inner wall and outer wall is 0.9m at the bottom of the pagoda and decrease to 0.6m gradually to the top. Two spiral stairs link the inner wall and outer wall and the staircase board is 4-5m in thickness.

The main pagoda is 23.25m in height over the ground and 1m under the ground and has the parapet which is 1.6m high on the top of outer wall. The small pagoda is 10.37m in height and takes the shape of Frustum of a Cone，with diameter on the bottom of the pagoda 2.0m long and matching perfectly with the outer surface of the inner wall. The top of the small pagoda takes the shape of conical, and 2.08m in height, with the diameter on the bottom of the pagoda is 2.0m.

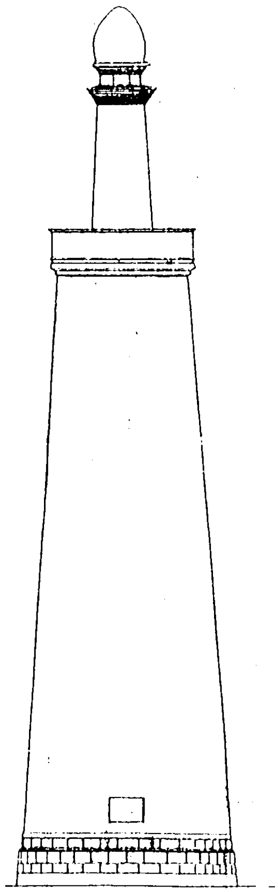


Fig.1 Sketch of ancient pagoda

2.3 History changes and existing state of the ancient pagoda

The small pagoda on the top had been destroyed by the hurricane and the body of the pagoda had been eroded over a long period of time. The pagoda has been repaired for several times and now the problems are as followings.

2.3.1 Declivity ratio being larger

According to the investigation, the shift value and declivity ratio of the whole structure, the main pagoda and the small one are showed in the Tab.1, now the pagoda is fundamentally stable and the main pagoda is tilting toward northwest, the small pagoda is tilting towards west.(as shown in Fig.2 and Fig.3a). A recent investigation reveals that some parts of the body of the pagoda protrude(as shown in Fig.3b), the platform on the top of the main pagoda is tilting and the main part and the affiliated part falling unevenly.

Tab. 1 shift value and declivity ratio of the ancient pagoda

	e_1(mm)	e_2(mm)	e_3(mm)	Declivity ratio/‰	Declivity angle	Diameter/m	Height/m
Main pagoda	1075			45.5	2.6°	8.53-5.06	23.634
Small pagoda		582		54.8	3.1°	2.45-2.00	10.612
Whole pagoda			1617	47.2	2.7°		34.246

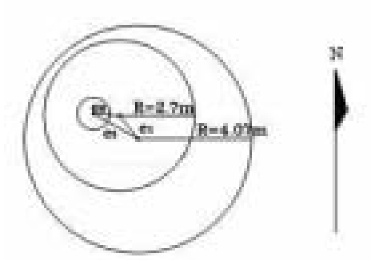


Fig. 2 Plan sketch of center of gravity of the pagoda

2.3.2 Base of the pagoda being falling

The two gate facing south and north of the main pagoda is 1.6m lower that the ground, mainly because of the falling of the ground base due to the water erosion.

2.3.3 Masonry separating in the ancient pagoda

The investigation on site shows that the outer wall of the main tower contains cracks distributed in vertical and lateral which is 6-8m in length, and 1-3mm in width, as shown in Fig.3c. The outer surface of the pagoda is falling and the top of the small one is damaged seriously, as shown in Fig.3d and Fig.3e.

(a) inclined pagoda (b) protruding of partial wall and vertical cracks (c) lateral cracks

(d) outer surface of wall falling (e) damage of small pagoda

Fig.3 Existing state of the ancient pagoda

2.3.4 Week connection between small pagoda and main pagoda

According to the investigation on the scene, the small pagoda is built on the inner wall of the main pagoda, and the connection between the two pagodas has not been given special treatment so as to lead to the less controlling of the main one to the small one, therefore, the small pagoda is not safety.

2.4 Strength test of masonry of the ancient pagoda

The body of the pagoda is built by solid bricks. In order to test the strength of the building materials, some specimen have been taken from masonry of the ancient pagoda to test in the laboratory. Those samples are taken from the outer surface of outer wall, the inner surface of the inner wall and the outer wall of the small pagoda. The samples taken are incomplete in their shape, their sizes are as followings (as shown in Tab.2) after being cut.

After the compressive strength tests on the cubic specimens taken from masonry, the results are shown in the Tab.2. Due to the strength of mortar very low, it is difficult to make test on site or in the laboratory. Therefore, it is recommended that the lowest strength grade of mortar may be taken, that is to say the strength of mortar can be considered to be M0.4.

Tab. 2 compressive strength of cubic and size of specimen

location	the size of specimen/mm	compressive strength of cubic/MPa
outer wall of main pagoda	65×62×60	2.6
inner wall of main pagoda	55×55×45	2.3
small pagoda	65×65×50	0.94

2.5 Field Measurement Study of dynamic behavior of the ancient pagoda

Method of tapping was used to cause vibration in order to take records conveniently and identify signals. Sensor of model 4381 made in Denmark and affiliated electric amplifiers are used. The sensor is put on the target point, and record the time history of acceleration of the ancient pagoda by DASP signal gathering apparatus.

The objective of the dynamic behavior test is to locate the test point according to the construction style and features of the ancient pagoda, thus nature frequency, Period and oscillation model of the ancient pagoda can be derived. The mass of the body of the pagoda is located evenly, so 10 accelerator sensors had been put from the bottom of the pagoda to the top, first from east to west, then from south to north. Ten tests had been made on every direction and taken ten minutes for every single test. The result of nature frequency, Period and damping of the ancient pagoda is shown in Tab.3.

Tab.3 Nature frequency, Period and damping ratio

oscillation model Number	1	2	3	4	5
Nature frequency /Hz	1.25	2.5	5.5	10.3	13.3
Period/s	0.800	0.400	0.182	0.097	0.0752
damping ratio	0.023	/	/	/	/

3. Mechanical properties of SMA material and damper

SMA is a new intelligent material with perceptional and driving function whose hyperelastic performance was utilized to develop a miniature SMA damper. The SMA damper can be installed on the ancient pagoda structure so as to execute passive aseismatic controls to depress the dynamic response under seismic action. Therefore, the mechanical properties of hyper elastic SMA wires and SMA damper are studied by experiments with variation of strain amplitude, loading rate, cyclic numbers and operated temperatures, and the actual energy-consumption capability SMA wires and SMA damper are examined.

3.1 Experimental study of Mechanical behavior of SMA wires

3.1.1 Manufacture and fabrication of SMA wire specimens

The SMA wire specimens are manufactured by Northwest institute for Non-ferrous Metal Research. The geometry of the SMA wire specimens is displayed in Fig.4. The diameter of specimens is 1mm, and the length of specimens is 150mm, the effective length is 100mm. chemical constitution is Ti-51at%Ni. Tensional cyclic loading tests were executed for total 68 specimens.

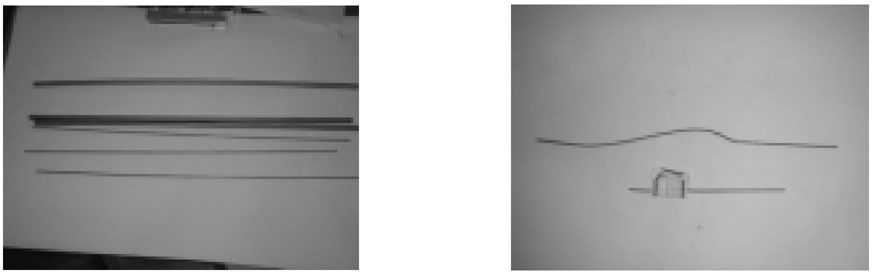


Fig.4 SMA wires for experiment and tearing specimens

3.1.2 Experimental apparatus

Micro-electronic controlled universal testing machine was used for the tests, as shown in Fig.5 and Fig.6. Various temperature circumstances were realized by an additional temperature control box with a temperature range of -50℃-50℃. Equal-displacement loading style was used for the cyclic tensile tests. All the result data were collected by the machine automatically.

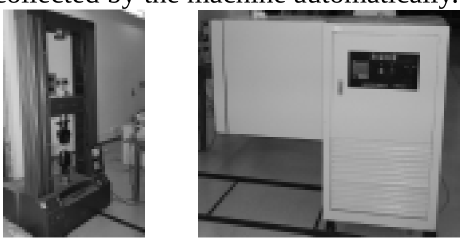


Fig.5 Testing machine with temperature control box Fig.6 Data collection system and SMA wire during test

3.1.3 Experiment result and analysis of the SMA wire specimens

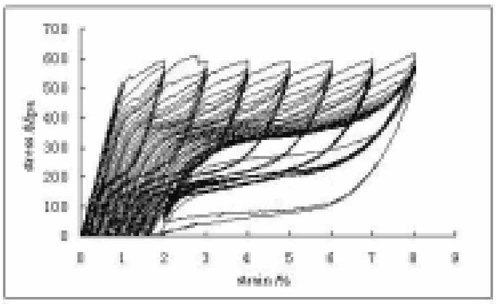


Fig.7 Typical SMA strain-stress curve under different strain amplitude

The results of the experiment show that strain amplitude, loading rate, cyclic numbers and operated temperatures will effect mechanical behaviors of SMA wire, such as equivalent secant stiffness, maximum unicyclic energy dissipating capacity and equivalent damping ratio in varying degrees. When the environment temperature rise from10℃ to 40℃, the change of equivalent secant stiffness of SMA wires is large and its growth rate is about 24.2%. But maximum unicyclic energy dissipating capacity and equivalent damping ratio are decreased by14.3% and 31% separately. The decrease rate is larger and the change of the SMA material's strain amplitude is also large. When strain amplitude is increased from 1% to 8%, maximum unicyclic energy dissipating capacity of SMA wire specimens will increase dramatically. The increase rate is near four times as large as the original one so that hysteretic curve of SMA wire specimen gradually plump and energy dissipating capacity increase notably.

The effect of loading rate and cyclic numbers on mechanical behavior of SMA wire material is relatively less. Generally speaking, through loading cycle in advance, the effect of cyclic numbers will be decreased. So the effect of loading rate and cyclic numbers can be neglected when using Heat Treatment Process and increasing loading cyclic numbers in advance, whereas the effect of the environment temperature and strain amplitude should be considered properly.

3.2 The study of SMA damper's mechanical properties

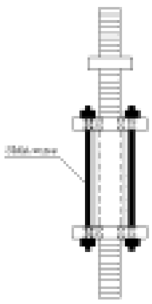
3.2.1 Processing and manufacturing of the SMA damper specimen

According to the dynamic characteristics of the ancient tower that needs to be strengthened, the reinforcement principle of the ancient construction and combined with its experiment result, three dampers were manufactured at this experiment. These are Damper of type A, Damper of type B and Damper of type C. Damper of type A is installed with six groups of SMA wires. Damper of type B and Damper of type C are installed with three groups of SMA wires separately.

The mainly distinction of type A and type C are the different number of SMA wires whereas the mainly distinction of type B and type C are the different length of SMA wires. The main design parameters of three type of SMA damper are shown in Tab.4and Fig. 8 gives a sketch of SMA damper and its actual photo.

Tab.4 Design parameters for SMA damper

Type of damper	Initial strain	Diameter of single SMA wire/mm	Number of SMA wire/n	Length of SMA wire /mm
A	3%	1.0	12	100
B	3%	1.0	3	50
C	3%	1.0	3	100



(a) Sketch of SMA damper

(b) SMA damper during testing

Fig.8 Photo of SMA damper

3.2.2 Experiment result and analysis of the SMA dampers

After processing the experimental data, force-displacement hysteretic curves of different types SMA dampers under various load case can be obtained. Experimental result displays SMA dampers possess good energy dissipating capacity having a plumping force-displacement hysteretic curve under different temperatures, loading rate and loading displacement range so as to be used widely in engineering ranges.

4 Shaking table test research of the ancient pagoda with SMA dampers

4.1 Model designing and manufacturing

The ancient pagoda is located on the district ,based on data in site, whose seismic fortification intensity is 7 degree, design basic acceleration of ground motion 0.1g，classification of design earthquake 1 group, site condition Ⅱ class and characteristic period of ground motion 0.35s. Considering the size and loading capacity of the shaking table, similarity coefficient of length was selected 1/10 and similarity coefficient of acceleration 2.73。

Shaking table test was performed for ancient pagoda model structures with El Centro, Taft and artificial ground motions which tuned into minor and moderate intensity of 7 degree being input to table, respectively, to investigate the seismic responses of the model.

Fig.9 pictures of model structure with and without SMA dampers

4.2 The results and analysis

When the SMA damper passive control system is installed at the top of the main tower in the Minaret model structure, the level effect for the top structure of the main tower and the small tower is not obvious under small earthquakes. It is mainly because the Minaret model structure itself deforms so slightly that it can not make SMA damper work at the ultra-flexible stage, which will not achieve energy dissipation and damping, only play the role of passive pull.

However, under stronger earthquakes, the top structure of the main tower will have a greater level displacement. This deformation makes SMA damper passive control systems work at the ultra-flexible stage because of being pulled. Repeatedly pulling makes SMA Damper fully play its excellent performance of energy dissipation. In addition, under stronger earthquakes, the top structure of the small tower also has a greater level displacement, which increases SMA damper passive control system to reduce level displacement of the top structure of the small tower effectively.

The vibration table test study about the Minaret model structure also shows that the model structure with SMA damper will not only reduce the displacement and acceleration response of the structure effectively, but also reduce the shearing force and deformation at the bottom of the main tower, which shows that the earthquake energy borne by the body of the tower originally has been absorbed partly by the SMA damper.

While the model structure with SMA damper can significantly reduce the overturning moment of the main structure to prevent the tower from further deforming, and reduce the cracks. In addition, the performance of SMA damper will be subject to various factors to varying degrees, including length of alloy wire, diameter, loading temperature, frequency and loading distance etc., so these factors will have a certain impact on the whole performance of the tower model structure with SMA damper.

5 Conclusion

The earthquake simulation vibration table test results about the model structure of ancient show that the installation of SMA dampers on model structure not only can reduce the displacement and acceleration response of the structure at the top of the main tower and the small tower effectively, particularly the reduce of displacement response is obvious, and the higher the intensity of the earthquake is, the greater the range of decrease is.

In addition, the installation of SMA damper can also reduce the earthquake shear force and deformation at the bottom of the main tower and can significantly reduce the overturning moment of the main structure to prevent the tower from further deforming and collapsing, and prevent the tower from cracking.

The test results show that the SMA damper and its passive control system has better energy dissipation effect, which can effectively improve the seismic capacity of ancient pagoda structure. It is worthy of being further developed and applied.

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