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STRUCTURAL RESPONSES OF HAKKA RAMMED EARTH BUILDINGS UNDER EARTHQUAKE LOADS

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Abstract: Hakka Tulou are rammed earth structures that have survived the material aging, natural weathering and strong earthquakes for hundreds of years. To understand the structural response of a Hakka earth building under earthquake-induced load, finite element (FE) analyses were conducted. First, the constituent materials of rammed earth wall construction, including rammed earth, and wooden and bamboo reinforcement strips that were used in the Tulou walls for increased strength, were collected during field study and tested under tension and/or compression in the laboratory for their strength and modulus of elasticity properties. Secondly, the volume fraction of reinforcement in a typical rammed wall was determined. From these material property data, the modulus of elasticity of the reinforced rammed earth wall was estimated using the Rule of Mixture. Thirdly, the structural responses of the entire rammed earth wall structure of Huanji Tulou under an earthquake loading were evaluated through FE modeling as per the simplified lateral force analysis procedure provided by ASCE-7, under three variations: 1) rammed earth wall construction without inner wooden structures, 2) reinforced rammed earth wall without wooden structures, and 3) rammed earth wall with wooden structures. In addition, the FE modeling of why and how the existing large crack of Huanji Tulou was formed under a strong earthquake load was conducted using the information collected from field study and the material property data generated from laboratory testing.

Keywords: Hakka Tulou, rammed earth, reinforced rammed earth, finite element analysis, earthquake resistance, structural response, ASCE-7, carbon dating, self-healing of crack, Huanji Tulou

1 INTRODUCTION

Rammed earth structures have existed on the planet Earth for thousands of years in regions that experience hurricane force winds and earthquakes. In these regions, civilization has seen modern construction appear to be the victim of nature's power whereas older rammed earth structures have been able to withstand those conditions through the test of time. Nowhere else is this situation more prevalent than in the Fujian Province of China which is prone to earthquakes. Here the Hakka Tulou have lasted for hundreds of years, outlasting newer construction. Since the 11th century, seven earthquakes of magnitude 5 or higher on the Richter scale have been recorded in the region. Some Tulou buildings have displayed cracks in their walls and broken roof tiles because of the earthquakes, however there has been no structural damage to any of the Tulous in the region. One specific example of a Tulou's resistance to an earthquake can be seen from the 1918 earthquake that registered at 7.0 on the Richter scale near the Huanji Tulou which was built in 1693. It was reported that this earthquake resulted in a crack on the rammed earth wall measuring 20 cm in width and 3 meters in length. The locals claim that this crack had self-healed as time passed by ever since the earthquake (Chinadaily, 2007). As part of our scope of research (see Liang et al, 2011), we closely examined this crack during the field trip in summer of 2009 and then conducted finite element analysis to understand how and why this crack was formed. We investigated if the self-healing of crack occurred and wondered if the massive rammed earth wall system integrated with inner wooden structures might have possibly contributed to, if any, the said self-healing phenomenon. The resulting FE model of Huanji Tulou was further used to investigate its earthquake resistance when the model was subjected to a design earthquake for the region as per code ASCE-7.

To conduct FEA at a reasonable accuracy, the strength and modulus of elasticity properties of the constituent materials of rammed earth wall construction including rammed earth, wooden and bamboo reinforcement were determined using the field-collected samples from 5 earth buildings and this was presented under section 3: Material Characterization. More information on Hakka buildings studied can be found in the paper by Liang et al (2011). Since many rammed earth walls were actually reinforced with either wooden or bamboo sticks like rebar in concrete construction, the volume fraction of such reinforcements in a typical rammed earth wall was estimated. Using the material property data for the rammed earth, wood, and bamboo, and the volume fraction of reinforcement data, one can use the Rule of Mixtures to find the modulus of elasticity of the reinforced rammed earth wall that will be used as inputs for FEA. The material property data of rammed earth wall samples generated from Material Characterization also reveal information on the material durability and structural integrity of Hakka buildings and can be used to compare with and correlate to the results obtained from nondestructive evaluation methods as discussed in a separate paper (Liang et al, 2011).

2 RADIOCARBON DATING AGE OF HAKKA TULOU

To validate the ages of the Tulou buildings and material samples that were reported among local official records, as a case study, a wooden sample from Chengqi Tulou was tested for its radiocarbon dating age. This wooden sample was cut from a roof truss beam in the Chengqi Tulou, reportedly built from 1662-1709, and was sent to the NSF- University of Arizona Accelerator Mass Spectrometry (AMS) Facility at the Department of Physics, University of Arizona, Tucson, AZ. The carbon dating measurement shows the sample at radiocarbon years 111 +/- 47 BP. Radiocarbon dates require calibration in order to transform them into calendar age ranges. The calibration plot for the sample tested is provided by NSF-Arizona AMS team and shown in Figure 1. The result indicates that there is a 95.4% probability that the sample is aged between the two calendar age ranges 1675AD -1778AD and 1799AD - 1941AD. This observation is consistent with the completion date of 1709 of Chengqi Tulou. Only the age of the wooden sample from Chengqi Tulou has been tested and verified while the ages of all other Tulou buildings reported herein are collected from local Government Records.

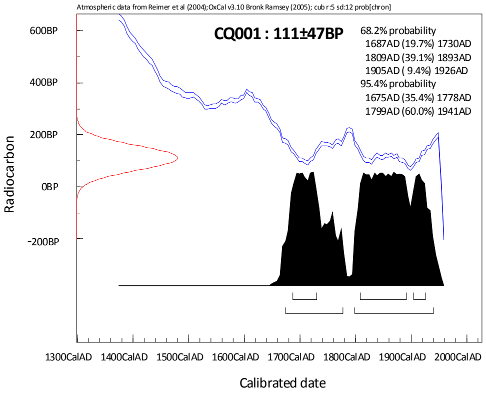


Figure 1: Carbon dating age of Chengqi Tulou

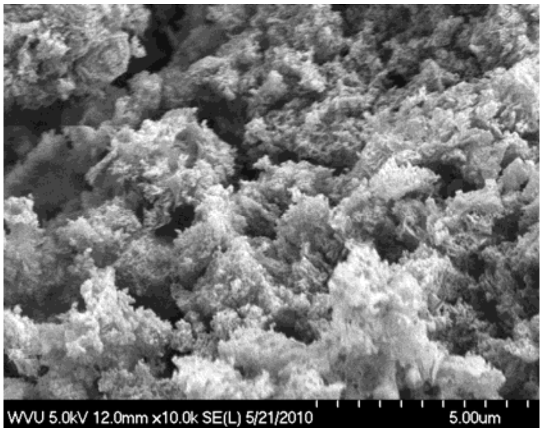


Figure 2: Fuxing Tulou earth sample SEM image

3 MATERIAL CHARACTERIZATION

In order to model the structural responses of Hakka Tulou, an understanding of the strength and stiffness of their constituent materials must be acquired. Samples of the constituent materials, including rammed earth, and wooden and bamboo reinforcement strips that were used in the Tulou walls for increased strength, were collected from the Tulou that were field–studied. It should be noted that the sizes of these samples were dictated by the dimensions of field samples, not necessary in accordance with the specimen requirements of ASTM standards. As a matter of fact, core extracts as per ASTM standard of the rammed earth walls from the Tulou were tried in field but not successful due to the rammed earth becoming brittle under the vibrations caused by the extracting equipment.

3.1 SEM and EDS Analysis of Tulou Rammed Earth Samples

In order to examine the composition of the rammed earth samples from various Hakka Tulou, Scanning Electron Microscopy (SEM) Hitachi SEM S-4700 with EDS attachment was used. The scanning electron microscope provides surface morphology of the earth samples at a micro to near-nano scale allowing us to compare surface property among rammed earth samples from different Tulous. Each sample was viewed and photographed at scales of 1mm, 300 micrometer, 200 micrometer, 10 micrometer and 5 micrometer. Figure 2 shows an image for Fuxing Tulou earth sample. After reviewing the SEM images of the earth samples from five Tulou it can be seen that each of the rammed earth samples looks fairly consistent from one viewing area to another. Except that Fuxing Tulou earth, which is over 1200 years old, has porous network type morphology (Figure 2), all others (Zhencheng, Chengqi, Wuyun, and Huanji Tulou) have mica-like flake surface structures. Chengqi and Wuyun Tulou earth samples have shown presence of wood fibers that were well bonded with surrounding earth (Figure 3) while Fuxing and Zhencheng Tulou earth samples are mixed with stone/rocks.

Energy-dispersive X-ray Spectroscopy (EDS) analysis can examine the chemical composition of a sample by showing the amount of existing elements relatively to each other in form of an elemental spectrum. Overlaid EDS charts for 5 Tulou earth samples studied are shown in Figure 4. From the EDS data one can see that all the samples from the five different Tulou show an abundance in oxygen, silicon, and aluminum (Note that gold in EDS chart comes from sample preparation coating to make the sample conductive, not from original earth samples). Three of the five Tulou, Zhencheng, Chengqi, and Wuyun, show an abundance of titanium while Chengqi and Wuyun Tulous also show significant amounts of carbon because of presence of wooden pieces. Even Zhencheng and Fuxing Tulous have phosphorous present whose roles are to be examined. As can be seen from the above varying results, the compositions of these samples are unique to what is locally available on site for each of the respective Tulous. This adds the complexity into discussion when comparing the rammed earth wall properties in terms of their varying ages.

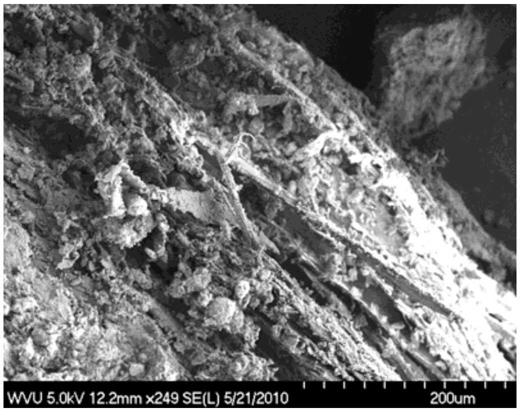


Figure 3: Wuyun Tulou earth sample SEM image showing wood fibers

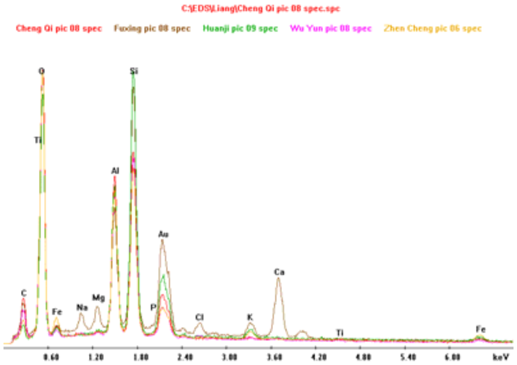


Fig. 4: Overlay EDS chart of 5 Tulou earth samples

It should be noted that the oldest Tulou, Fuxing, displays different spectrum from remaining four Tulou and shows an abundant amount of calcium while Wuyun and Chengqi have small amounts of calcium. Calcium comes in lime and subsequently is a constituent material of the walls prepared by the Hakka people. This large amount of calcium in the Fuxing Tulou earth sample explains the high strength of the walls and that the Fuxing Tulou has survived for over 1240 years.

3.2 Compression Properties of Rammed Earth

Rammed earth samples from the main wall structures of five Tulou were extracted and tested. Figure 5 shows representatively Chengqi Tulou earth sample after testing and resulting stress/strain curve. Table 1 summarizes the results of the rammed earth compression tests performed by both WVU and XMU. Note that testing of

Huanji Tulou earth samples did not result in reliable property data because of their brittle nature. As shown in Table 1, it is amazing that the rammed earth sample from the oldest Fuxing Tulou has strength and stiffness equivalent to those of the younger Chengqi and Zhencheng Tulou. On contrast, the rammed earth sample from Wuyun Tulou at 500 years in-service, has the lowest strength and stiffness, likely due to prolonged weathering effects as well as the composition of the material. This, among many other factors, helps explain why part of Wuyun Tulou's front rammed earth wall is leaning inward and currently needs structural retrofit.

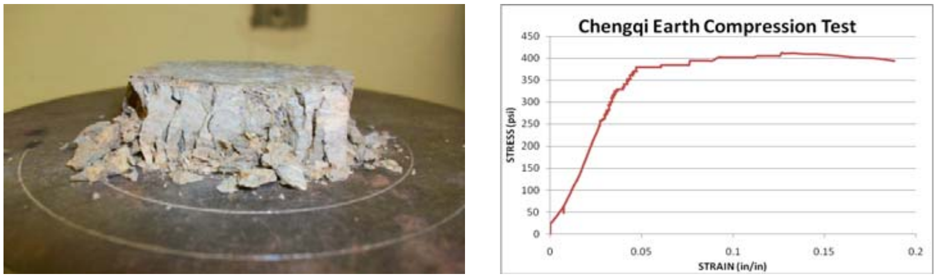


Figure 5: Chengqi earth sample after compression testing and resulting stress/strain curve

Table 1: Rammed earth compression properties

		Xiamen University		WVU	
Tulou	Age (years)	E (psi)	f'c (psi)	E (psi)	f'c (psi)
Fuxing	1240	6318.1	282.4	X	X
Wuyun	500	1705.5	133.1	2129.3	278.8
Chengqi	300	X	X	8147.1	411.1
Zhencheng	100	3597.9	196.0	4291.4	125.9

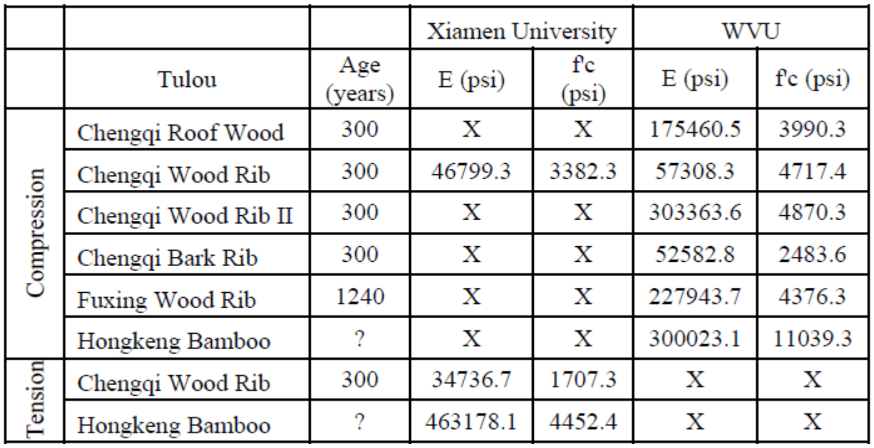
Fig.6: Exposed wall ribs

The Fuxing Tulou at 1240 years in-service is very strong and hard, and has the highest compressive strength (282 psi) and modulus of elasticity (6318 psi) among the samples tested by Xiamen University. The PI (Liang) talked to the owner of Fuxing Tulou in person during field study. As per the owner, in 1970's it took two people as a team 16 days to make an opening for a window and 40 days for a side door. The Fuxing Tulou rammed earth wall is built of a composite mixture known as "Sanhetu" that includes red soil, lime, and pebbles. Some articles indicate that soupy glutinous rice and brown sugar are added in some wall systems (Ostrowski, 2007). When the PI talked to Tulou owners, they don't agree with that statement. Our EDS spectrums are not able to verify that statement either. In case of Fuxing Tulou, the rich amount of lime/calcium simply explains why the earth wall has become so hard with time.

3.3 Tension and Compression Properties of Wood and Bamboo Samples

It is generally believed that rammed earth walls are reinforced with bamboo strips and wood branches at a given pattern of spacing. Significant number of wooden pieces can often be seen from outer and inner wall surface. They act as reinforcing bars known as wall-ribs in the rammed earth walls in the same manner as rebars in the modern concrete constructions. They were placed while the wall was being constructed. Such wooden and bamboo pieces were field collected and tested by both Xiamen University and West Virginia University for their mechanical properties. Table 2 shows the test results of wood and bamboo reinforcement strips as well as structural wood that were used in the inner structures of the Hakka Tulou. Having the modulus of elasticity and strength data for the constituent materials of rammed earth wall construction allows one to more reasonably model the material and structural responses of a Hakka Tulou using Finite Element programs as well as compare the current property data of the material to those typical values of the same material. However, in order to use the Rule of Mixture to determine the property of the reinforced rammed earth, the volume fraction of reinforcement is needed.

Table 2: Mechanical properties of Tulou wood and bamboo samples



			Xiamen University		WVU	
	Tulou	Age (years)	E (psi)	f'c (psi)	E (psi)	f'c (psi)
Compression	Chengqi Roof Wood	300	X	X	175460.5	3990.3
	Chengqi Wood Rib	300	46799.3	3382.3	57308.3	4717.4
	Chengqi Wood Rib II	300	X	X	303363.6	4870.3
	Chengqi Bark Rib	300	X	X	52582.8	2483.6
	Fuxing Wood Rib	1240	X	X	227943.7	4376.3
	Hongkeng Bamboo	?	X	X	300023.1	11039.3
Tension	Chengqi Wood Rib	300	34736.7	1707.3	X	X
	Hongkeng Bamboo	?	463178.1	4452.4	X	X

3.4 Determining Volume Fraction of Reinforcement in Rammed Earth Wall

To estimate the volume of reinforcement in a typical rammed wall, a cross section of rammed earth wall was identified with pultruding bamboo wall ribs and shown in Figure 6. Dimensions of the exposed wall ribs, their spacing, and the wall thickness were field-measured and used to estimate the volume of reinforcement for this particular wall, also known as the fiber volume fraction that is needed in order to model the structural response of Tulou.

Based on the samples collected, the wooden rib samples were typically round and varying at around 1.5 inches in diameter, which results in a fiber cross section of 1.767 in^2 while bamboo rib samples were in rectangular strips with dimensions typically around 0.5 inch x 1 inch, which results in a fiber cross section area of 0.5 in^2. If one is to assume that the same spacing is used for both wood reinforcement and bamboo reinforcement as exhibited by the exposed wall ribs in Figure 6, then the volume fraction for wood reinforcement comes out to be 6.7% and the volume fraction for bamboo reinforcement to be 1.8%. Using the strength and stiffness property data of reinforcements and rammed earth along with the above volume fraction of reinforcement, the modulus of elasticity for a reinforced rammed earth wall can be calculated as per the Rule of Mixture.

4 THE WALL CRACK OF HUANJI TULOU

Huanji Tulou has an O/D 43.2m and 20m in height. It was reported that there was a 3m long crack of 20 cm in width due to a strong earthquake in 1918 that was self-healed after quake. As a matter of fact, the large crack is still on the wall. The reported earthquake-induced crack is about 10 meter above the ground. A global view of this crack is shown in Figure 7a. The crack begins from the 3rd floor window, across the 4th floor window and thru the top edge of rammed earth. To access and examine the crack, a construction worker was hired to build an access platform using bamboo during the field study in the summer of 2009, as shown in Figure 7b. After measuring the crack, including use of a laser distancer to measure its depth, the researchers found that the crack was about 350 cm in height including the crack thru the 4th floor window, with the crack between 4th floor window and 3rd floor window being the worst. That section was 178 cm in height, 5 to 10 cm in width, and 93 cm in depth. As shown in Figure 7c, this crack was actually across the entire wall thickness and most surprisingly, there were no wall ribs at all inside the rammed earth wall.

4.1 Has the Crack Self Healed?

If in fact the crack was originally 20 cm in width as initially reported, there could be some kind of self-healing process that should possibly be explained scientifically. In order to further analyze the structural behavior of the Hakka Tulou buildings, FE modeling was used to duplicate the structural behavior experienced in real world conditions (Stanislawski, 2011). A 3D model was built using the modulus of elasticity values reported in Table 1 as well as actual dimensions of the Huanji Tulou. The modulus of elasticity used was taken from Wuyun

Tulou samples as this value is most conservative and no property data available for the earth samples from the Huanji Tulou. Also included in the model is the reported 20 cm wide crack that is 3 meters in length.

Figure 7: Huanji Tulou wall crack after earthquake, a) a global view of the crack, b) the crack location with reference to the ground and the access platform used during field study, c) close view of the crack

The round rammed earth walls were created in a finite element modeling program in order to see how thermal effects, such as thermal expansion, impact the autogenous healing process. The internal wooden structure of the Tulou initially was not modeled and instead can be assumed to restrain, to a certain extent, the thermal effects experienced on the rammed earth walls. For the model, boundary conditions were assumed accordingly; at the base of the rammed earth walls the conditions most closely follow a fixed connection as the rammed earth walls tie in directly to either earth or stone foundations that are common amongst Hakka Tulou. The top of the rammed earth wall was assumed to act as a pinned connection as the wooden roof structure ties into and lies on the top of the rammed earth wall. The roof connection is flexible and allows rotation which is the reason for the pinned connection rather than a fixed connection at this location. It is important to understand that these are theoretical boundary conditions whereas in reality the boundary conditions are a balance between the restrained and free conditions. A temperature load was applied across the entire model in order to see the thermal effects of the structure knowing the thermal expansion coefficient as well as using the assumed boundary conditions. A thermal expansion coefficient of a clay brick of $3.3*10^{-6}$ in/in/°F was assumed satisfactory for the analysis of the rammed earth walls (Friedman, 2006).

The model was subjected to either 70 F thermal variation or -70F temperature load thermal contraction, how the crack deforms in response to thermal loads was noted. Under the cooler thermal load, it can be seen that the crack is actually shrinking in width. The -70°F load would close the crack by over half at the most extreme point, i.e. 10.8 centimeters, leaving a crack width of 9.2 centimeters. This temperature effect does not however explain the autogenous healing of the rammed earth as healing of the crack is simply reversed when the temperature goes back up. Temperature is thus found not to be the sole factor in the autogenous healing process, rather an important part of the process (Stanislawski, 2011).

Autogenous healing has been researched for several decades in common building materials such as concrete. Current research regarding autogenous healing of concrete has mostly portrayed the healing of small cracks or micro cracks experienced in concrete systems. The key ingredient to the autogenous healing process is lime. As cracks appear in concrete systems, water infiltrates the cracks and dissolves any lime that it may come in contact with. The dissolved lime is then taken to the surface of the crack where it carbonates and begins to heal the crack (Rhydwen, 2007). The key component to lime is calcium. However, Figure 4 EDS chart for Huanji Tulou indicates no calcium in its rammed earth.

Infrared Thermography (IRT) camera was originally planned to be used to verify if there were any self-healing response of a crack-after-quake as discussed in (Liang et al, 2011). We assumed that the wall was reinforced with wall ribs. We proposed to use the IRT technique to scan the crack area. If the crack was truly self-recovered, a section of wall would have debonded wall rib from surrounding earth. Even there might be cavities at some ends of wall ribs if not fully recovered. Unfortunately it was found by the researchers during field study that Huajian Tulou was not reinforced by any wood strips and IRT was found not sensitive to identify the debond between wall rib and rammed earth.

Considering the scale of this crack, we would like to doubt if there was such story-telling self-healing. One observation from our close-examination of the crack can be drawn from Figure 8. It was noticed that there is a 5 cm cavity at lintel end. If the wall would have self-healed 5 cm, that cavity and most of the crack would disappear. Hence, we would like to interpret the fame of Huanji Tulou as the strongest Tulou as follows: Even though Huanji Tulou had such a large cross-thickness crack, it is still structurally sound. Why the crack occurred with Huanji Tulou is most likely because it does not have reinforcing wall ribs in its rammed earth wall.

Figure 8: The crack and cavity at lintel end

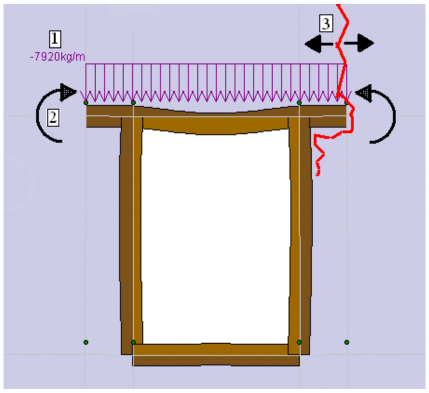


Figure 9: Lintel behavior

4.2 Modeling the Crack Formation

The crack at the Huanji Tulou reportedly occurred due to a strong earthquake that hit the region. The crack began at the end of a window lintel due to high stress concentrations occurring from bending of the upper portion of the lintel. Why and where exactly the crack formed (Figure 8) has been accurately modeled using FE analysis, based on Lintel behavior as shown in Figure 9 along with an earthquake load, using the material property data generated from this study (Table 1). Figure 10 is a chart illustrating the stress in vertical direction upon application of a 220 kips horizontal load induced by an earthquake. Details can be found in (Stanislawski, 2011). Through the FE modeling one can see exactly how an earthquake load can cause increased loading in the Tulou and in return cause higher stresses leading to potential cracking. The FE modeling further demonstrated that if the rammed earth wall of Huanji Tulou were reinforced with wall ribs, such cracking could be totally avoided. Cracking could have also been avoided by using a stiffer lintel. This might explain why other Hakka Tulous in the area survived from the earthquake even without cracking.

Since both round and square Tulous have performed outstandingly under earthquake loads, we suspect if the large mass of outer walls together with the integrity of internal wooden structure is a contributing factor for their excellent earthquake resistance. The structural response of the entire rammed earth wall structure of Huanji Tulou under an earthquake loading is evaluated thru FE modeling and presented in Section 5.

5 STRUCTURAL RESPONSE UNDER AN EARTHQUAKE LOAD

The Hakka Tulou have survived strong earthquakes for hundreds of years. To understand their earthquake resistance, a model of the Huanji Tulou was used for earthquake analysis. In order to model the behavior of the Tulou during an earthquake, the simplified lateral force analysis procedure provided by ASCE-7 was used (ASCE7, 2005). The simplified lateral force procedure is typically used for frame type structures no taller than three stories as this method focuses on base shear rather than the dynamic response from an earthquake. The base shear that results from an earthquake is of primary concern for short structures as dynamic effects control for taller structures. The Huanji Tulou being modeled is four stories tall with a height of 20 meters. Due to the thickness of the walls and resulting high mass of the rammed earth, it can be assumed that a simplified lateral force analysis will be sufficient for the structure as dynamic effects will be minimized. The resulting calculations shown are thus the effects of base shear being distributed throughout the four floors of the structure. By distributing this base shear throughout the structure one can then analyze the stress induced into the rammed earth walls by a design earthquake for the region. Initially, only the thick rammed earth walls and their self weight are considered during modeling. Then the rammed earth walls combined with internal (inner) wooden structures (floor systems) are further modeled to better reflect the response of actual Tulou buildings. Since the modulus of elasticity of 1705.5 psi was used for the rammed earth in the model as no property data available for rammed earth samples from the Huanji Tulou, this analysis is being taken as the most conservative. The effect of rammed earth strength including effect of reinforcement and types can be found in (Stanislawski, 2011).

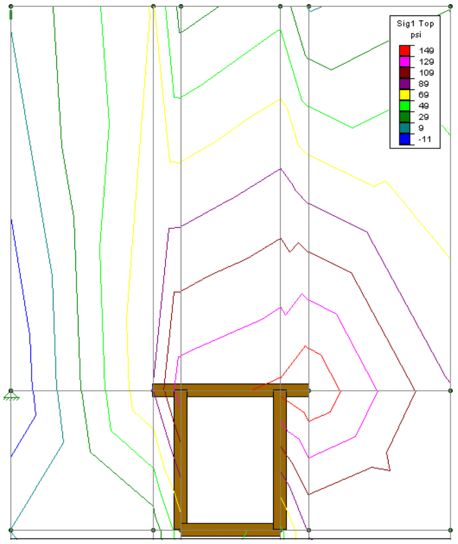


Figure 10: Stress in vertical direction due to horizontal load induced by Earthquake

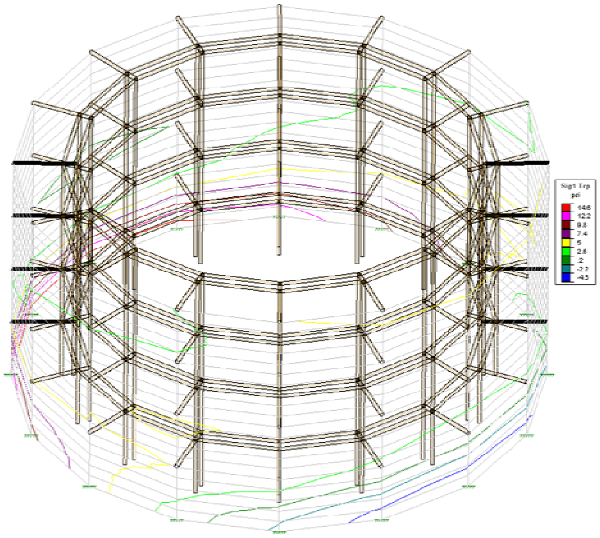


Fig 11: 3D Earthquake stress distribution of Huanji Tulou with inner wooden systems

There are two important equations that are used in the simplified lateral force analysis and both can be seen Equations 1 and 2, respectively (ASCE7, 2005):

$$V = \frac{F\, S_{DS}}{R} W \tag{1}$$

$$S_{DS} = \frac{2}{3} F_a S_S \tag{2}$$

Equation 1 calculates the base shear from a design earthquake and can be distributed throughout each floor of the structure by changing ‘W’ to be the effective seismic weight of the structure at that floor of interest. ‘R’ is simply the response modification coefficient which will be taken as 1.5 for a bearing wall system made of ordinary plain masonry walls, this factor was chosen as it most resembled the conditions of a rammed earth wall. ‘F’ is a factor that depends on the structure height, since this method is used for a maximum of three stories, the upper value of 1.2 for three stories was used for analysis purposes. ‘S_{DS}’ is a design spectral response acceleration at short periods, 5% damped, which can be calculated using Equation 2. ‘F_a’ is the short period site coefficient at 0.2 seconds which can be found in a table knowing both ‘S_s’ and site class of the area of interest. Since the site class is unknown, ASCE-7 states that one can classify the site as class D unless geotechnical data determines that class E or F are present. ‘S_s’ is the mapped spectral response acceleration, 5% damped, at a period of 1 second (ASCE7, 2005).

The Global Seismic Hazard Assessment Program (GSHAP) has compiled seismic maps from all around the world. The seismic map for China was created by the Chinese government in 1992 and shows peak ground acceleration which has a 10% chance of exceeding marked intensities in 50 years (Zhang et al, 1999). From the seismic China map, the peak ground acceleration for the Fujian Province varies from 0.8-1.6 m/s^2. This map also coincides with an earthquake report on China performed by Lanbo Liu (2001), in which he states no major post Paleozoic tectonic activity has been found in the region and thus seismicity for the Fujian province is low. No maps of spectral response acceleration for the China region were found. ASCE-7 allows one to convert peak ground acceleration, PGA, to the mapped spectral response acceleration, 'S_s', by simply multiplying the PGA by a factor of 2.5. To be conservative, a PGA of 1.6 m/s^2 was multiplied by 2.5 to get an 'S_s' value of 4. ASCE-7 states that 'S_s' need not be taken higher than a value of 1.5 which results in a short period site coefficient, 'F_a', of 1.0. By plugging in the 'S_s' and 'F_a' values of 1.5 and 1.0 into Equation 2, one gets a 'S_{DS}' value of 1.0. One can then plug this 'S_{DS}' value back into Equation 1, which simplifies into what can be seen in Equation 3:

$$V = .8W \tag{3}$$

Equation 3 calculates the base shear force for the entire structure. A density of 1600 kg/m^3 was used for rammed earth as with previous modeling. Knowing the density, height of 20 meters, as well as the area of the Huanji Tulou (1.8 m thick wall, outer diameter 43.2 m) results in a total weight of the structure of 7.49 x 10^6 kg (16.5 x 10^6 lbs) which results in a total base shear of 5.99 x 10^6 kg (13.2 x 10^6 lbs). To find the vertical distribution of the force that is applied to each floor of the structure, we must use the total base shear and input it into Equation 4:

$$F_x = \frac{w_x}{W} V \tag{4}$$

In Equation 4, 'w_x' represents the portion of the effective seismic weight of the structure. Since our structure has 4 evenly spaced floors, the force per floor is equal to ¼ of the total base shear which is equal to around 1.5 x10^6 kg (3.3 x10^6 lbs) per floor. Divivided by 16, which is the amount of nodes used to create the circular model, the resulted per node lateral load for each of the four floors turns out to be 93,645 kg (206,452 lbs). These loads are applied in a simaltaneous direction on all 16 nodes for each floor in order to represent the effects of a maximum considered earthquake that can be expected in the Fujian Province.

Stress analysis was performed using the maximum principle stress theory. This theory states that the material will yield when any of the principle stresses reaches the yielding stress (Benham and Warnock, 1973). Through numerous testing it has been found that the maximum stress theory works best for predicting failure in brittle materials such as concrete, cast-iron, and ceramics (Benham and Warnock, 1973). As rammed earth is a brittle material, analysis of the material will be performed using this maximum stress theory. Figure 11 shows the stress distribution on the model Tulou integrated with wooden structures after applying the lateral forces to each floor. The stress distribution in Figure 11 shows the stress, σ_1, which is the stress in the vertical direction of the wall. The σ_2 distribution is simply a mirror image of the σ_1 stress distribution.

As can be seen in Figure 11, for the model Tulou combined with inner wooden structures, a maximum compressive stress of 14.6 psi occurs near the base of the Tulou in the σ_1 direction which coincidently means that a maximum tensile stress of 14.6 psi occurs near the base at the opposite end of the Tulou in the σ_2 direction. Note that if the rammed earth walls are considered alone (without inner wooden floor structures), the maximum stress is 141 psi near the base of the Tulou. These models and results are conservative as the lowest modulus of elasticity of 1705.5 psi was chosen from all rammed earth samples tested. Realistically however, since the Huanji Tulou is one of the younger Tulou structures at 300 years of age the modulus of elasticity of the rammed earth is most likely to be higher and thus ultimate strength is most likely to be higher as well. If one is to analyze the stress data above and compare the data to ultimate strength values that range from 126 psi to 411 psi as found in compression testing (Table 1), one can see that the strength of the rammed earth walls is 9 to 28 times higher than the maximum value of 14.6 psi from the modeling. Failure would not be expected even at/near the base of the structure where the maximum tension and compression stresses occur as predicted by the model. It is important to note that only ultimate compressive strengths are known for the rammed earth and that tensile strength of such materials is surely lower than its compressive strength, for this reason the structure would fail in tension at the base, sooner than it would in compression, if the earthquake induced stresses were equivalent to the ultimate tension strengths of rammed earth walls. It should also be noted that many rammed earth walls are reinforced with wood chips and as discussed at Section 3.4, those wall ribs greatly enhance the earth walls.

Hence, the rammed earth construction makes the structures strong as the walls are high in volume which cause material stresses to be kept low and away from failure zones. The thick rammed earth walls integrated with internal wooden floor structures resist the design earthquake very well. As a matter of fact, the rammed earth wall is built in a taper design with the base much thicker and the top thinner, instead of an uniform thickness from the base to top as used in the model. The tapered wall design not only offers the wall with better structural stability, but also higher earthquake resistance, more efficient use of materials, and optimal thermal comfort.

Seeing as how the model used the maximum design earthquake for the region, lowest modulus of elasticity for rammed earth, it can be seen by both modeling and history that the high mass of the Hakka Tulous does a very efficient job of dissipating energy under earthquake forces.

6 CONCLUSIONS

In this paper, finite element modeling was conducted to simulate the material and structural responses of Hakka Tulou under earthquake loads for a better understanding of their outstanding earthquake resistance. Huanji Tulou has a large crack on the rammed earth wall reportedly due to a strong earthquake in 1918. Local people claimed that crack was self-healed and thus Huanji was known as the strongest Tulou. The research team first closely examined that crack during the field study in the summer of 2009, followed up with FE modeling. That crack began at the end of a window lintel and was found to be cross- through the entire wall thickness. The computer modeling has successfully simulated why and how exactly the crack was initiated and further developed under an earthquake induced load. The FE modeling further demonstrated that if the rammed earth wall of Huanji Tulou were reinforced with wall ribs, such cracking could be totally avoided. This study also concluded that there was no self-healing of the crack after earthquake. The fame of Huanji Tulou as the strongest Tulou should be interpreted as follows: Even though Huanji Tulou had such a large cross-thickness crack, it is still structurally sound. However, the FE modeling has demonstrated that the Hakka Tulou does offer superior earthquake resistance because of its unique rammed earth wall construction that makes the structures strong and cause material stresses to be kept low and away from failure zones.

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