

Final Report for Period: 01/2011 - 06/2011

Submitted on: 09/27/2011

Principal Investigator: Liang, Ruifeng .

Award ID: 0908199

Organization: WV Univ Research Corp

Submitted By:

Liang, Ruifeng - Principal Investigator

Title:

SGER: Material and Structural Response of Historic Hakka Rammed Earth Structures

Project Participants

Senior Personnel

Name: Liang, Ruifeng

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: GangaRao, Hota

Worked for more than 160 Hours: No

Contribution to Project:

Post-doc

Graduate Student

Name: Stanislawski, Daniel

Worked for more than 160 Hours: Yes

Contribution to Project:

Reprocessing field data, conducting RISA FE modeling and thermal comfort analysis, and preparing draft report

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

Prof Ying Lei

Xiamen University, Xiamen, China

To co-organize International Workshop on Rammed Earth Materials and Sustainable Structures & Hakka Tulou Forum 2011: Structures of Sustainability in conjunction with International Symposium on Innovation & Sustainability of Structures in Civil Engineering, October 28-31, 2011, Xiamen University, China

Activities and Findings

Research and Education Activities:

Rammed earth is a sustainable building material with several positive environmental attributes compared to concrete and steel. The in-service World Heritage Hakka Tulou rammed earth buildings, in the Fujian Province of China, are unique in design and performance. Those buildings have thick (~2 m) outer rammed earth walls and inner wooden structures making up floors and rooms, are three to five stories in height, round or square in shape, and have hundreds of rooms housing up to 800 people. There are many illustrative photographs and travel logs about Tulous' characteristics and architecture. The UNESCO's inscription as World Heritage recognizes their artistic, cultural and historic significance. Through this study, engineers from West Virginia University in collaboration with Xiamen University of China investigated the engineering and scientific values of those buildings in terms of low energy consumption but still comfortable living, sustainability, and durability.

The material and structural responses of Hakka Tulou buildings under thermal and mechanical (including earthquake) loads were field-investigated using nondestructive testing techniques. The durability of rammed earth walls of several rammed earth buildings was investigated in terms of in-situ strength measurements using rebound hammer and ultrasonic testing device. Infrared thermography was employed with intention to study the rammed earth/wall reinforcement bond but was found not sensitive enough to reveal any useful information. Instead, the volume fraction of wall reinforcements was determined using a cross section of wall with pultruding wall ribs. The earthquake resistance of Hakka Tulou was examined thru a case study of Huanji Tulou. It is reported that a strong earth quake in 1918 resulted a large crack in the rammed earth wall of Huanji Tulou. The locals claim that the crack had self-healed afterwards. The researchers closely examined this crack after building a platform to access the cracking area. The structural integrity was evaluated thru in-situ full scale load testing on roof truss and floor systems. The strain data on roof truss and floor members (beams and columns) were collected as a function of loads. Climate data including temperature and humidity were collected in Chengqi Tulou using thermocouples and data loggers. The thermal data were needed for thermal comfort analysis of living in a Hakka Tulou.

Then the field data were re-processed at West Virginia University (WVU) and integrated with new data generated from material characterization of field collected samples at both laboratories of WVU and Xiamen University. Finite element analyses were conducted to simulate those material and structural responses to arrive at better understanding. More specifically, the research activities during the phase of campus study included the following: 1) Radiocarbon dating test was conducted to validate the ages of the Tulou buildings and material samples that were reported among local official records; 2) Mechanical characterization of rammed earth, wood and bamboo samples was conducted that were collected from the field?study during June 15-July 15, 2009; 3) Scanning Electron Microscopy and Energy-dispersive X-ray Spectroscopy analyses of Tulou rammed earth samples were carried out to examine the composition and morphology of the rammed earth samples from various Hakka Tulous; 4) Field data on the strength and stiffness of rammed earth walls from rebound hammer and ultrasonic testing device were reprocessed and compared with the strength and stiffness property data generated from laboratory materials testing; 5) The strain data of floor and roof systems from load tests were reprocessed in comparison with finite element modeling results using RISA 2D program; 6) The computer modeling of why and how the large crack of Huanji Tulou was formed under an earthquake load was carried out using the info collected from field study and the material property data generated from laboratory testing; 7) The structural response of the entire rammed earth wall structure of Huanji Tulou under an earthquake loading was evaluated thru FE modeling as per the simplified lateral force analysis procedure provided by ASCE-7; and 8) The secrets behind Hakka people living in comfort in Tulou buildings in summer and winter without use of electricity were examined thru thermal comfort analysis based on the field data collected in the summer of 2009.

In addition, the first Hakka Tulou Forum: Lessons to Be Learned, Past, Present and Future was organized on June 24, 2009 at Xiamen University, China where the International Hakka Tulou Alliance was also launched at the same time. The objective of the 2009 Forum was to demonstrate how the sustainability of Hakka village architecture built hundreds of years ago and still in-use today, would bridge the past, present and future, with lessons for our modern world. As the second event of Hakka Tulou Forum Series, the International Workshop on Rammed Earth Materials and Sustainable Structures, as a special session of the International Symposium on Innovation and Sustainability of Structures in Civil Engineering (ISISS'2011), is going to take place from October 28 to 31, 2011, Xiamen University, Xiamen, China. This workshop brings together experts from Australia, Canada, China, Japan, UK and USA to examine the research potential of rammed earth materials and structures with emphasis on strategies to implement rammed earth in modern constructions with its inherent environmental and structural stability and sustainability. The third Hakka Tulou Forum: Putting Sustainability into Practice will be organized from June 29 to July 1, 2012, Toronto, Canada.

Findings: (See PDF version submitted by PI at the end of the report)

Hakka Tulous are rammed earth structures that have survived the material aging and natural weathering for over 1000 years. The objectives of this study were to better understand the thermo-mechanical and aging response of those Hakka Tulous under thermal and earthquake loads through nondestructive field evaluation including full-scale roof truss and floor testing, laboratory testing of field samples and finite element analysis, with emphasis on potential benefits of the rammed earth material's near-zero embodied energy (consumed), high thermal mass, and outstanding structural performance and potential implementation of Hakka material selection and construction principles in modern

constructions.

As a result of this exploratory research, we have arrived at a spectrum of technical findings on the material and construction choices, durability, structural integrity and thermal comfort of historic Hakka Tulou rammed earth buildings. Some major findings are: 1) Hakka Tulous have excellent earthquake resistance, because of its unique rammed earth wall construction integrated with inner wooden floor structures that makes the wall systems strong and causes stresses to be kept low and away from failure zones; 2) There is no self-healing of the earthquake-induced crack on Huanji Tulou, that is a large, cross-the-wall-thickness crack, even though local people claimed that crack was self-healed. The FE modeling demonstrated that if the rammed earth wall of Huanji Tulou were reinforced with wall ribs, such cracking could be totally avoided; 3) Fuxing Tulou's outstanding strength and durability is due to abundance of calcium from lime in its earth wall formulation, while other buildings do not use lime in their walls; 4) Ultrasonic device appears to be viable to quantitatively compare the strength of rammed earth walls in a timely, nondestructive manner ; 5) The full scale load testing result and structural analyses conclude that both the floor and roof truss systems are structurally sound and the jointed neighboring members have a high load-sharing effect with the load-carrying beam that can be better idealized through simple beam with fixed end model as opposed to a simple beam; 6) The Hakka people found ways to live in thermal comfort without the need of mechanical heating in winter or cooling in summer due to their effective use of rammed earth construction. The rammed earth walls actually can 'breathe' and regulate not only room temperature but also humidity; and 7) Hakka Tulou rammed earth walls are not always reinforced with wood branches or bamboo strips. For those with wall ribs, the volume fraction of reinforcement is estimated to be 6.7% for wood or 1.8% for bamboo.

Our findings may lead to using Hakka principles to build more disaster resistant structures and also shed light on new approaches applicable to LEED projects. Modern construction can simulate the Hakka construction techniques and make rammed earth construction a viable building material option of the future. Part of our work was featured by US History Channel/AETN 'History, Made for Tomorrow - Hakka Tulous', 2010, A&E Television Networks LLC.

A complete description of our research activities and findings as a result of this exploratory research can be found in the appended full length technical paper.

Training and Development:

One graduate student of US origin, Daniel Stanislawski, Civil and Environmental Engineering at WVU, was employed as a graduate research assistant on the project. Daniel re-processed the field data and conducted finite element modeling to simulate the material and structural responses of Hakka Tulou rammed earth structures, including thermal comfort analysis. Daniel also contacted our China partner from time to time for information exchange. He completed his thesis, entitled 'Mechanical Response and Finite Element Modeling of Hakka Tulou Rammed Earth Structures' and graduated in May 2011. During the course of this study, Daniel was extensively exposed to Hakka Tulou architecture and associated Hakka culture. It proved a good opportunity and unique experience to him when interacting and exchanging with another completely different culture. Surely he has been trained to understand material and construction choices of Hakka Tulou structures and hopefully will arrive at potential extension of Hakka technology to modern construction involving earthquake-resistant, hurricane-proof and energy-efficient structures.

Outreach Activities:

The Hakka Tulou Forum 2009 attracted over 130 undergraduate students and many of them feeded back to the PIs of their interests in and thoughts on rammed earth as a material and construction technique.

The History Made for Tomorrow film produced by US History Channel/AETN, featuring part of our work is going to be broadcast on TV programs.

Journal Publications

Books or Other One-time Publications

Liang, R, G. Hota, D. Stanislawski, Y. Lei, Y LI, and Y. Jiang, "Material and structural response of historic Hakka rammed earth structures", (2010). Conf Proceedings, Published
Collection: Proceedings of the 85th Annual Meeting of the West Virginia Academy of Science, Morgantown, West Virginia, 10 April, 2010
Bibliography: WVAS

Liang, R, G Hota, Y Lei, Y-H Li, D Stanislawski, and Y-Q Jiang, "Nondestructive evaluation of historic Hakka rammed earth structures", (2011). Conference Peer Reviewed Paper, in print

Editor(s): Ruifeng Liang

Collection: Proceedings of Int. Workshop on Rammed Earth Materials and Sustainable Structures, Oct 28-31, Xiamen University, China

Bibliography: ISSS 2011

Liang, R, D Stanislawski, G Hota, "Structural responses of Hakka rammed earth buildings under earthquake loads", (2011). Conf Peer Reviewed Paper, in print

Editor(s): Ruifeng Liang

Collection: Proceedings of Int. Workshop on Rammed Earth Materials and Sustainable Structures, Oct 28-31, Xiamen University, China

Bibliography: ISSS 2011

Stanislawski, Daniel, "Mechanical response and finite element modeling of Hakka Tulou rammed earth structures", (2011). Thesis, Published

Collection: Electronic Thesis

Bibliography: MSCE Thesis, West Virginia University

Liang, Ruifeng (Ray), Hota GangaRao, Daniel Stanislawski and Ying Lei, "Thermal and mechanical responses of Hakka Tulou rammed earth structures: Lessons to be learned for a sustainable future", (2011). Conf Paper, Published

Editor(s): NSF CMMI

Collection: Proceedings of 2011 NSF Engineering Research and Innovation Conference, Jan 4-7, Atlanta, Georgia

Bibliography: NSF CMMI

Web/Internet Site

URL(s):

<http://www2.cemr.wvu.edu/~rliang/ihta/ihta.htm>

Description:

This site is still being developed and will present all papers and all events as a result of the NSF award. The PIs wish thru this site to help disseminate the research findings and facilitate the potential extension of Hakka technology to modern construction.

Other Specific Products

Product Type:

Audio or video products

Product Description:

History, Made for Tomorrow - Hakka Tulous, produced by US History Channel/AETN, 2010, A&E Television Networks LLC.

History, Made for Tomorrow is AETN new community outreach program to show case historic places where lessons can be learned to build a sustainable 21st century.

The film featured WVU work along with those of Jorg Ostrowski of ASH and Minoru Ueda of MU Design. Support from NSF to WVU work is acknowledged.

Sharing Information:

This film will be broadcast on AETN network channels worldwide.

Contributions

Contributions within Discipline:

Rammed earth is a construction material and technique with a favorable life cycle impact on the planet Earth. Our study will help make the engineering community aware of the advantages of rammed earth construction, bring to their attention what rammed earth is capable of, and promote new research opportunities that can further advance our knowledge on the material for modern construction.

Contributions to Other Disciplines:

Our study indicates that the sustainability of Hakka village dwellings built hundreds of years ago and still in-use today can provide us with new approaches with reference to green building movement including Leadership in Energy and Environmental Design (LEED) program. The Hakka Tulou rammed earth construction technology can be emulated with appropriate modifications for implementation in modern construction leading to: 1) energy-efficient and green buildings with thermal comfort; 2) disaster resistant structural configurations; and 3) innovations of affordable housing and multi-story buildings.

Contributions to Human Resource Development:

One American graduate student was trained with knowledge of rammed earth material and construction. This project also helped promote cross-culture exchange.

Contributions to Resources for Research and Education:

Thru this project, we started a Hakka Tulou Forum series. Hakka Tulou Forum 2009: Lessons to Be Learned, Past, Present and Future took place on June 24, 2009 at Xiamen University and was concluded with a great success. Hakka Tulou Forum 2011: Structures of Sustainability is going to take place on Oct 28-31, 2011, Xiamen, China. Hakka Tulou Forum 2012: Putting Sustainability into Practice will be organized on June 29 to July 1, 2012.

Contributions Beyond Science and Engineering:

Much of the value of this research is the recognition of the potential viability of using rammed earth structures to meet the needs for sustainable affordable rural communities and to fuse historical techniques to advanced building science to meet today building and environmental standards.

Conference Proceedings

Categories for which nothing is reported:

Organizational Partners

Any Journal

Any Conference

Final report of NSF grant CMMI #0908199

NONDESTRUCTIVE EVALUATION OF HISTORIC HAKKA RAMMED EARTH STRUCTURES

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September 26, 2011

Abstract: The in-service Hakka rammed earth buildings, in the Fujian Province of China, are unique in design and performance. The UNESCO's inscription as World Heritage recognizes their artistic, cultural and historic significance. Sponsored by National Science Foundation of the United States, the authors have investigated the engineering values of those buildings in terms of low energy consumption but still comfortable living, sustainability, and durability. The objective of this study was to better understand the thermo-mechanical and aging responses of Hakka earth buildings under thermal and earthquake loads through nondestructive field evaluation including full-scale roof truss and floor testing, laboratory testing of field samples and finite element modeling. The scope of work included: 1) identification of constituent materials in rammed earth and investigation of durability of the constituents; 2) investigation of structural integrity of Hakka buildings for structural efficiency under extreme loads, including potential modes of failure and verification (if any) of the reported self-healing of cracks; 3) analysis of heat transfer process through rammed earth wall for thermal comfort and energy-efficiency; and 4) evaluation of potential benefits of the material in terms of embodied energy (consumed) and structural performance for potential implementation in modern constructions.

Keywords: Hakka Tulou, rammed earth, reinforced rammed earth, earth structures, finite element analysis, earthquake resistance, ASCE-7, carbon dating, self-healing of crack, load test, load sharing, thermal comfort, NDE, nondestructive evaluation, ultrasonic, rebound hammer, Infrared thermography

1 INTRODUCTION

Rammed earth construction is a widespread, ancient technique where soil is taken from the ground and compacted between vertical wooden frameworks (molds), which are then removed leaving an earth wall. Many historic rammed earth structures are either in service or abandoned, in many countries, e.g., China, India, Spain, Morocco, Yemen, Egypt (Jaquin, 2008). Recently rammed earth has been attracting significant interest again as a sustainable construction material because of its numerous benefits to the environment compared to concrete and steel (NAREBA). For example, the Desert Living Centre, outside Las Vegas, has been constructed from rammed earth and aims to provide Nevada residents with information on sustainable living.

Hakka rammed earth buildings (also known as Tulou), in the Fujian Province of China, reflect the emergence of innovation, evolution, and advancement in the engineering of rammed earth construction from the 8th to 20th centuries. Those earth buildings have thick (~2m) outer rammed earth walls and inner wooden structures making up floors and rooms, are three to five stories in height, round or square in shape, and have hundreds of rooms housing up to 800 people. Since 1980s, thousands of visitors (including professionals and scholars) have visited Hakka earth buildings, resulting in many illustrative photographs and travel logs about Tulou's characteristics, architecture including defense devices and fire

walls, and construction techniques. It is worth noting that Aaberg, a Danish architect, visited Hakka earth buildings in 1997 and reported the architecture marvel of those structures (Aaberg, 2000). More recently, Ostrowski, a Canadian architect has been researching ecological footprint of Hakka earth buildings which are considered “green” in terms of their planning, design, construction, lifestyle, resource management, renewable energy, and modest ecological footprint (Ostrowski et al, 2007). However, people have underestimated the engineering value of those buildings in terms of low energy consumption for comfortable living, sustainability, and durability (Liang et al, 2009).

A group of engineers from West Virginia University (WVU) and Xiamen University (XMU) of China traveled to Hakka villages in Yongding, Fujian province of China from June 15 - July 15, 2009 and field-studied several representative Hakka earth buildings as listed Table 1. The studies were conducted in a nondestructive (NDE) manner using techniques and equipment such as Infrared Thermography (IRT) Scanning Camera, Rebound Hammer, Ultra-Sonic Testing Device, strain data acquisition for load tests on the wooden roof truss and floor systems, and thermal data acquisition including humidity data from thermocouples. The data collected from the field were further processed at WVU and XMU for their implications along with the data generated through testing the field-collected samples at both WVU and XMU laboratories, including carbon dating.

Table 1: Hakka earth buildings studied

Title of Tulou	Shape	Number of Story	Age	Status
Fuxing Tulou	Square	2 story	over 1200 years	partially in service
Wuyun Tulou	Square	4 story	over 500 years	partially in service
Chengqi Tulou	Round	4 story	over 300 years	in service
Huanji Tulou	Round	4 story	over 300 years	in service
Zhcheng Tulou	Round	4 story	about 100 years	in service

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.

3 MATERIAL CHARACTERIZATION

In order to better model the structural responses of Hakka Tulou, an understanding of the strength and stiffness of their constituent materials must be acquired. The material property data of rammed earth wall samples 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 Section 4.

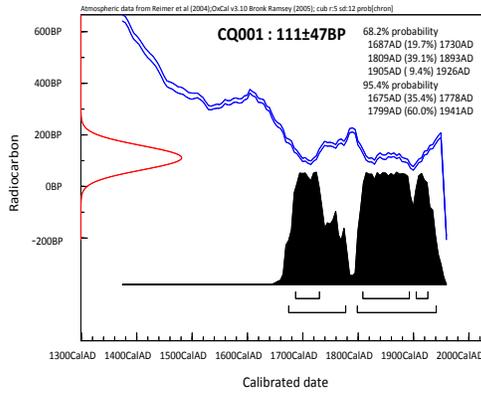


Figure 1: Carbon dating age of Chengqi Tulou

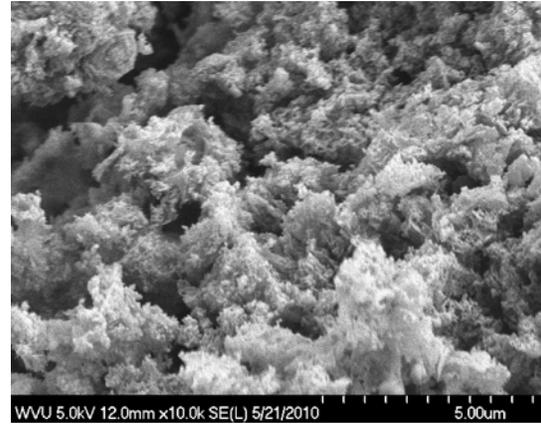


Figure 2: Fuxing Tulou earth sample SEM image

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 Tulou. 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.

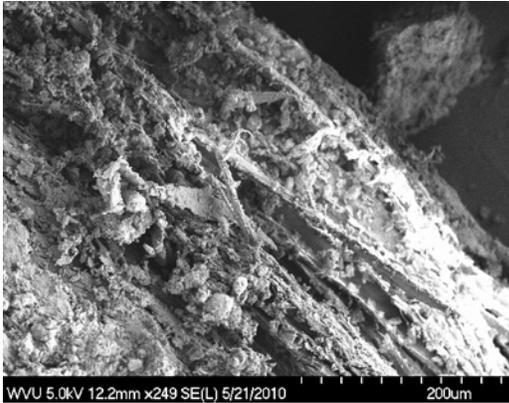


Figure 3: Wuyun Tulou earth sample SEM image showing wood fibers

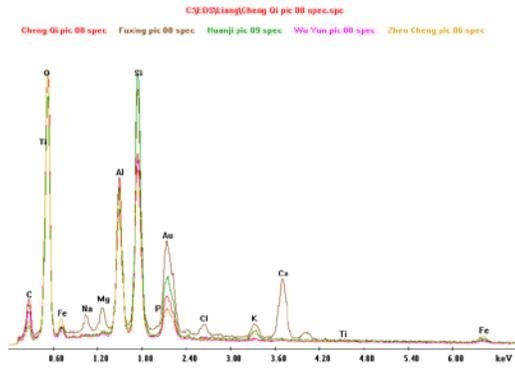


Fig. 4: Overlay EDS chart of 5 Tulou earth samples

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 2 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 2, 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.

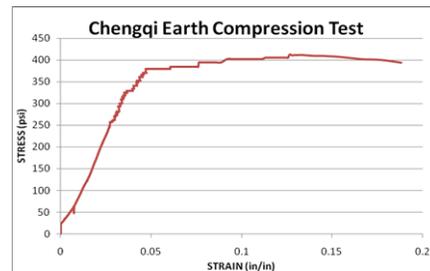


Figure 5: Chengqi earth sample after compression testing and resulting stress/strain curve

Table 2: Rammed earth compression properties

Tulou	Age (years)	Xiamen University		WVU	
		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 3 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. This was discussed next sub-section.

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 in² 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 in². 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.

Table 3: Mechanical properties of Tulou wood and bamboo samples

	Tulou	Age (years)	Xiamen University		WVU	
			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

4 NONDESTRUCTIVE EVALUATION OF RAMMED EARTH WALLS

Nondestructive evaluation (NDE) techniques refer to those methods that enable the testing of materials/ structural components without impairing their future usefulness or the testing and long-term monitoring of in-situ structures (Halabe et al, 1995). Because of the nature of the present study, NDE testing was necessary as to be able to assess the conditions of the rammed earth walls, without damaging the historic structures. Both an ultrasonic testing device and rebound hammer were employed to field-evaluate the wall systems and collect data to better understand the durability and structural integrity of rammed earth walls in a comparative manner. In addition, Infrared Thermography Scanning Camera was also used with intention to detect the bonding status between earth and wall rib, while thermal couples and data loggers were used to collect temperature and humidity data to be discussed in Section 5.

4.1 Ultrasonic Method

Ultrasonic testing is a NDE test which can tell us the strength of the material as well as if defects are present in the material. A wave, in this case produced by an ultrasonic transducer, will travel through a material such as the rammed earth wall and be detected by a receiver (as shown in Figure 7). The way how the wave propagates can give valuable information with respect to the structural integrity of the structure being tested. More specifically, the velocity of the wave is a function of the material's properties such as stiffness, density, and Poisson's ratio as well as the presence of defects. Similarly, the amplitude of the wave sent through a material is expected to be higher through a more "sound" material or a material that shows fewer defects. A combination of velocity and amplitude measurements provides more useful information by increasing the sensitivity of the ultrasonic technique to defects. In most cases a decrease in wave amplitude represents a possible defect. One can compare the velocity of a wave to the amplitude to see if there are inconsistencies. If inconsistencies exist then there is a possibility that a defect may be present (Halabe et al, 1995).

Figures 8 and 9 show the ultrasonic velocity and amplitude results for the buildings tested. Both charts are consistent and show the same trend. This most likely means that no large defect exists in the areas of the material that were tested and that the readings may reflect the strength of the materials. Note that each data point represents an average of 25 to 30 measurements. As can be seen in Figs 8 and 9, apparently, there is no direct correlation between the age of the Tulou structures and the velocity/amplitude (the strength of the rammed earth walls) of the ultrasonic wave. Other than the age, there are many more parameters in the wall system varying from one Tulou to another, including different earth constituents, with or without wall ribs, and varying construction quality.

A useful discussion on these NDE data can be made with reference to the mechanical properties and other testing results of the rammed earth wall samples that were generated in the laboratory that are discussed in Section 3. Ultrasonic data indicate Zhencheng earth wall has the highest strength. This observation is generally supported by the SEM and static test results. Wuyun has higher velocity than Fuxing and Huanji. Huanji Tulou earth sample is brittle and the researchers were not able to prepare any specimens of a regular shape. Thus, Huanji Tulou earth sample would have the lowest strength among the buildings studied. Contradictorily, Fuxing Tulou earth sample has been proven strong and hard. Its lowest ultrasonic velocity should be attributed to the fact that all the measurements from Fuxing were conducted on wet walls because of raining weather during field study and the earth wall might have become soft. Having the above points in mind, the Ultrasonic testing result does agree with the mechanical properties of the earth wall samples



Fig 7: Ultrasonic testing heads and device

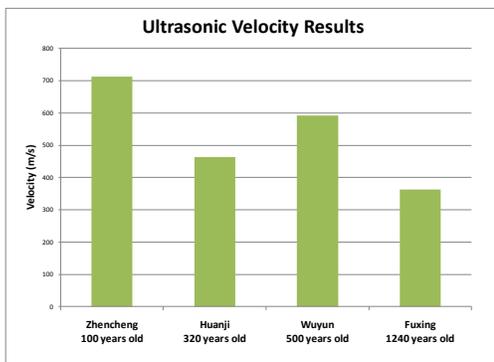


Fig 8: Ultrasonic velocity results*

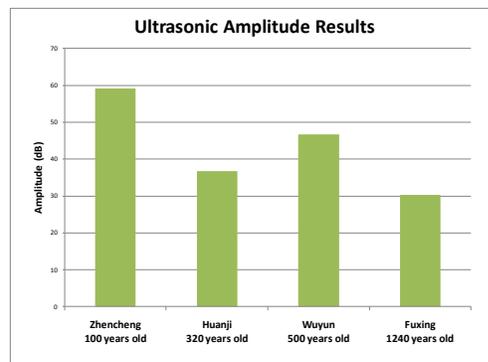


Fig 9: Ultrasonic amplitude results*

*Fuxing Tulou data obtained on wet walls due to rain

4.2 Rebound Hammer Method

As per ASTM C805, a rebound hammer works as follows: A steel hammer impacts, with a predetermined amount of energy, a steel plunger in contact with a surface of concrete, and the distance that the hammer rebounds is measured. This is shown in Figure 10. During the field study, two types of rebound hammers were used, one specifically for brick and another specifically for mortar. Figure 11 shows the results of the rebound hammer test. Note that Rebound Hammer is not designed for rammed earth wall but offers a method to quantitatively evaluate the strength of Tulou earth walls. Each data point represents an average of 32 to 64 readings in case of rebound hammer measurement. Also, all the measurements from Fuxing were conducted on wet walls because of raining weather during field study and its value was likely underestimated. In a similar manner dealing with the ultrasonic data, the discussion on the rebound number can be made with reference to the strength and modulus data of the rammed earth wall samples reported in Section 3 of this report.



Fig 10: Rebound Hammer

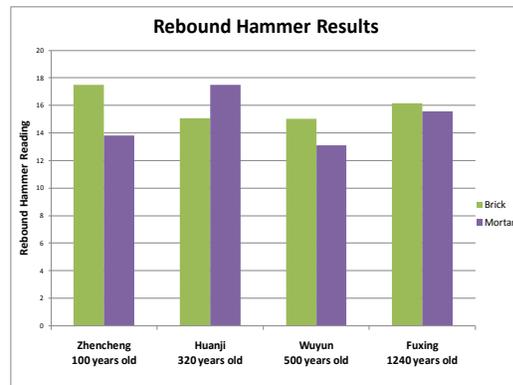


Fig 11: Rebound Hammer results

*Fuxing Tulou data obtained on wet walls due to rain

As shown in Figure 11, the average rebound hammer readings do not show any correlation between age of the Tulou and hardness of the material tested. Apparently, the brick rebound hammer represents the conditions of the rammed earth wall more accurately than the mortar rebound hammer with reference to the experimental modulus data of the rammed earth walls. According to the brick rebound hammer values, the Zhencheng would have the highest modulus of the elasticity, followed by Fuxing, and the Wuyun and Huanji would have similar low modulus values. Except for Huanji where the mortar rebound hammer average reading was much higher than the brick rebound hammer, for other Tulou, the brick rebound hammer always gave higher average reading than the mortar rebound hammer. Note that each value is a statistical average over a number of measurements.

For the purpose of this project, nondestructive testing using ultrasonic or rebound hammer should effectively tell us a quantitative comparison of the strength of rammed earth walls between the different Tulou tested. However, without a calibration chart of the ultrasonic device/rebound hammer for the rammed earth wall, these tests were not able to yield material strength values to be compared to those values determined from material tests. Instead, a comparison of NDE data with experimentally determined strength data of the rammed earth walls, would establish the confidence for further wide use of such NDE techniques.

Both types of NDE data do not reveal a direct correlation between the strength of the rammed earth walls

and the age of the structures. Other than the age, each rammed earth wall was constructed using resources locally and preparing the wall materials differently. The deterioration rate of each wall with increased exposure to the environments and other aging factors would be different, pending on the quality of the rammed earth wall construction. For example, Fuxing Tulou is at an age of 1240 years but its rammed earth wall retained strength higher than those of the Wuyun Tulou which is 500 years old and Zhenzheng Tulou which is 100 years old. What is remarkable of this characteristic is that at such old age one would be surprised to find a local domestic material be able to retain such strength. This situation however raises more questions as some earth walls were reinforced with bamboo or wood sticks that also have a serious impact on the strength of the rammed earth wall. Overall these rammed earth walls are amazingly strong and hard. The rammed earth wall of such level of hardness even broke two lock rings on a new hammer drill while making a 3/8" hole in order to place a thermal couple close to the center of Chengqi Tulou wall during field study.

4.3 Infrared Thermography Scanning Method

Infrared thermography (IRT) is a viable NDE method potentially capable of scanning a large area of testing structure and detecting subsurface delaminations and debonding between the surface layer and the substrate. This technique is based on the principle that subsurface defects and delaminations affect the overall thermal conductivity of the material, leading to different rates of heat transfer through sound and defective regions and thus, surface temperature differentials. For the present study, a brand new portable IRT camera model InfraCAM SD Camera was purchased (shown in Figure 12) and brought to China for field studies.



Fig 12: Portable IRT camera used

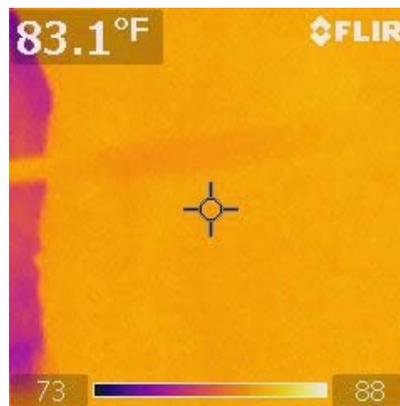


Fig 13: IRT detecting shallow wall rib

IRT camera was intended to perform a couple of functions upon verification of its usefulness during field study. One function would be to identify the presence of a wall rib with reference to a wall without wall ribs. If successful, we would be able to quantify the spacing, pattern, size and total volume of wood or bamboo wall ribs used as reinforcement within the rammed earth walls. Unfortunately, it was found that the IRT was not sensitive enough to detect the difference in the heat transfer rate between the walls with or without wall ribs. This is because the constituent materials to build a rammed wall, including earth, wood, bamboo, stone and others are all natural materials. Under a normal condition, they are all thermally in equilibrium. The surface temperature difference between the walls with or without wall ribs is almost zero, especially when the wall ribs are embedded in depth away from the wall surface and the wall has a thickness of 1.5 to 2 meter. Note that IRT is only able to identify defects under subsurface (at a limited depth). For example, the IRT is indeed able to detect the wall rib as shown in Figure 13 where a slightly dark shadow represents the wall rib, when the wall is around 12" in thickness with a crack in the vicinity. Due to crack, wind effects and shallow embedment of the rib in the wall, the temperature difference

between the wall rib embedding area and its surrounding just meet the camera's sensitivity (~0.5C).

Another expectation for the IRT camera was to try if it were able to detect the good or bad bond between the rammed earth and wall rib. For the same reasons as stated above, the IRT camera was not sensitive enough to identify if the bond between the earth and wall rib is good or not either. The temperature gradient in no way is big enough between those two conditions. During field study, cold water was spread onto the rammed earth wall with intention to signify the difference in heat transfer rate but was not effective.

A third intention was to use IRT camera to verify if there was any self-healing response of a crack-after-quake from Huanji Tulou as discussed in depth in Section 7. Unfortunately it was found 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. Hence, no positive results were generated from the IRT camera.

5 THERMAL COMFORT ANALYSIS OF LIVING IN HAKKA TULOU

Within the walls of Hakka Tulou, many families live in comfort both in summer and winter. The Fujian Province lies at the end of the temperate zone closest to the equator, meaning that the region has four seasons throughout the year. The winters tend to be very mild while the summers are fairly hot.

In this case of thermal analysis the heat transfer is from conduction, which means that heat energy is transferred from molecule to molecule until temperature equilibrium is reached. There are two particularly important properties of a material that can control the process of conduction and in turn control the thermal comfort of any structure. These properties are known as the thermal resistivity and thermal mass of a material. The thermal resistance of a material is the ability of a material to resist heat flow, meaning that the higher the thermal resistance of a material, the more the material will resist temperature change with respect to its surrounding temperature. Thermal mass meanwhile is the ability of a material to absorb and release heat in an attempt to reach a thermal equilibrium with its surrounding area (Reardon et al, 2008). It is well known that materials with high thermal mass have relatively low thermal resistivity and thus are not good insulators. Materials that typically have high thermal mass and thus absorb a lot of heat energy in order to change temperature are high density materials such as concrete, brick, and in this case rammed earth.

Table 4: Temperature data of Chengqi Tulou (Field collected July 1, 2009)

Temperature data (F)	Location of thermocouple						
	Court yard	Inside room	Inner wall surface	Inside inner wall	Inside outer wall	Outer wall surface	Outer yard
Time							
10:50	80.2	80.2	81	79.9	81.9	88	82.9
12:00	81.5	79.7	81	79.9	82.2	89	84
13:30	82.4	79.5	83	79.9	82.9	95	89.6
15:20	82.9	79.5	81	80.1	84.7	112	96.1
18:00	82.6	79.7	80	80.1	90.7	101	96.6

In order to illustrate how effective the use of high thermal mass has been implemented in the Hakka Tulou, temperature and humidity data were recorded. During July 1, 2009, temperature and humidity readings

were recorded at Chengqi Tulou by West Virginia University and are shown in Tables 4 and 5. Seven day period temperature and humidity data obtained using Data Loggers at Chengqi Tulou from June 29 to July 6, 2009 were presented by Ueda (2011).

Table 5: Humidity data of Chengqi Tulou (Field collected July 1, 2009)

Time	Location of humidity sensor				
	Court yard	Inside room	Inside inner wall	Inside outer wall	Outer yard
10:50	74	78	82	66	71
12:00	74	80	82	65	69
13:30	69	79	82	49	60
15:20	69	79	81	32	53
18:00	69	79	81	38	46

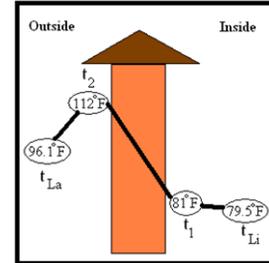


Fig 14: Chengqi Tulou temp profile

Table 4 shows temperatures recorded at different locations at the Chengqi Tulou, i.e. outside the Tulou, the outer and inner rammed earth wall surfaces, and inside an interior room. As can be seen from Table 4, the hottest that the outer surface of the rammed earth wall ever reached was 112° F with a temperature profile inside and outside Tulou shown in Figure 14. Since this is the most extreme temperature difference, this set of temperatures from 15:20 can be used to calculate the thermal resistivity in situ, giving a thermal resistivity of 1.0986 m.K/W (Stanislowski, 2011).

More commonly, materials are rated on their thermal resistance, which is denoted as the ‘R’ value. The ‘R’ value represents the ability of a material per unit thickness to resist heat flow. The higher the ‘R’ value the more the material is resistant to heat per unit thickness. To calculate the ‘R’ value of the entire rammed earth wall we use the thickness of the rammed earth wall at the Chengqi Tulou of 1.8 meters and multiply it by the thermal resistivity, resulting in a ‘R’ value of $11.24 \frac{ft^2 \cdot F \cdot hr}{BTU}$. To get this ‘R’ value into the standard ‘R-#’ format that is used to rate materials in the United States, one must divide this ‘R’ value by the thickness of the rammed earth wall in inches, while keeping the units in the current ‘R’ value the same. By following this operation the rating for thermal resistivity of the rammed earth wall is found to be R-0.16 per inch which means that the thermal resistance is $0.16 \frac{ft^2 \cdot F \cdot hr}{BTU}$ for every inch of rammed earth wall (Stanislowski, 2011). Hence, the rammed earth is not a good thermal resistor.

Hakka Tulou have no insulation from their rammed earth walls and instead must rely on the high thermal mass that rammed earth provides. Materials that have a high density such as concrete and rammed earth require more heat energy to change their temperature while materials with low density such as wood do not need a lot of heat energy in order to change temperatures. A successful application of thermal mass is one in which internal temperatures of a structure are kept stable when compared to varying temperatures from the outside. For example, during the warm summer season a material with high thermal mass should absorb the heat from the outside while keeping the interior cool during the day. At night the material with high thermal mass should release the heat to keep the interior temperature stable when compared to the colder night temperatures outside. During the winter the material with high thermal mass should be heated by direct sunlight in order to release heat and keep the interior temperatures at a comfortable level (Reardon et al, 2008). These thermal comfort benefits have also been observed in cave dwelling (Watanabe, 2003). Seven day period climate data (Ueda, 2011) clearly show that while temperature or humidity fluctuates outside, the interior temperature or humidity remains constant at a comfortable level throughout the entire week. As observed from WVU and Ueda data, the thermal comfort zone is achieved due to the effective use of thermal mass from the rammed earth walls.

6 STRUCTURAL EVALUATION OF FLOOR AND ROOF SYSTEMS

When discussing the structural integrity of Hakka Tulou, attention must be turned to the inner wooden structures. The inner wooden structures carry the loads that are experienced within the Tulou, as well as external loads such as wind loads, and distribute these loads to both the rammed earth walls and the interior wooden columns.

6.1 Full Scale Floor System Testing

The floor system of a Tulou building consists of a number of columns, beams and floor panels (Figure 15). Each load carrying member is jointed to each other through pinned connection. All horizontal beams are connected around the inner yard to make a circle. The focus of this set of load testing is to better understand how the floor member responds to an external load and how the load is distributed among the neighboring members.

The floor load testing was conducted between the 3rd and 4th floor of Chengqi Tulou in the following steps: 1) identify representative structural units for the test; 2) mount a number of strain gages at appropriate locations; 3) connect strain gages to the multi-channel strain data acquisition; 4) apply load gradually and take readings from each channel under each loading; 5) download gradually and take readings; and 6) repeat the uploading and downloading tests 3 to 4 times. The geometric dimensions of all the members were measured. The weights used were bags of metal clamps that were borrowed from a nearby restoration site (Wuyun Tulou). Each bag was 27.5 lb and total 20 bags were used.

The floor system of Chengqi Tulou was tested by means of a two point load of up to 550 lbs. The test section of the floor is shown in Figure 15 along with a schematic illustration where each member is assigned with a number (M1 to M7) and strain gage locations are indicated. The load was applied onto Beam M6 between Column M2 and Column M3 as two equal concentrated loads symmetrically placed.

Load testing of such structures is also a form of nondestructive testing that allows us to evaluate the material and structural responses of a structure under external loads without damage to the structure itself. The results will reveal how structurally sound a structure may or may not be. In order for a better understanding of the structural responses, one can conduct FE analyses and compare the strain gage data from the load test to the strain/stress values from an FE model. In this study, RISA 2D software was employed to model the responses of the floor and roof systems (Stanislawski, 2011).

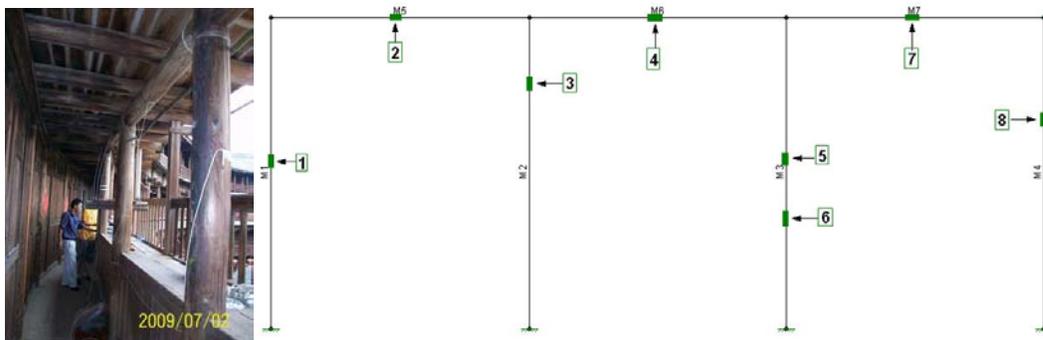


Fig 15: Load testing of floor system, member definition and strain gage locations

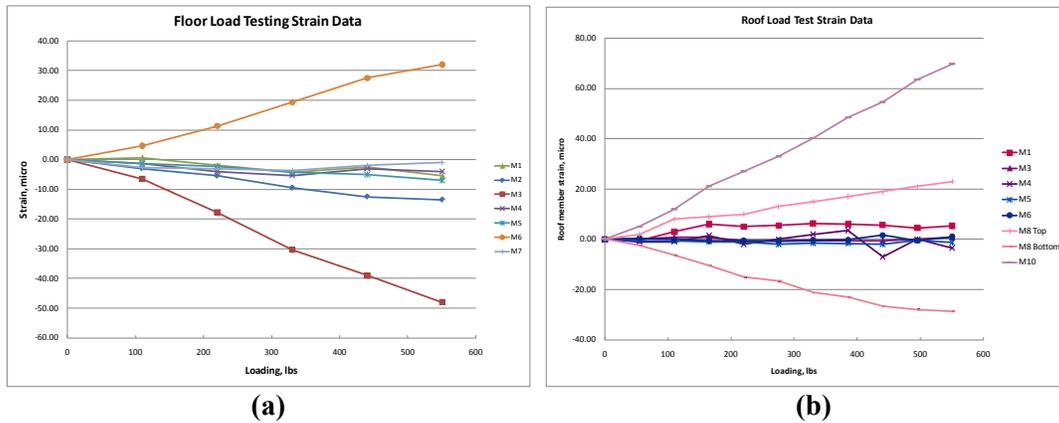


Fig 16: Strain data from load tests, a) floor system member strain data; b) roof truss member strain data

The strain data generated from the floor testing are graphically shown in Figure 16a, in terms of the strain gage locations and corresponding structural members as defined in Figure 15. The strain was recorded as a function of loadings for each member. Each strain value at a given loading was an average of three measurements from three separate runs. The load applying member M6 (gage #4) behaved as expected and gave a strain of 32 microstrain under maximal loading of 550 lbs. All other members had small strain values except the vertical member M3 (gage #5) that had unusual much higher values and gave a strain of 48 microstrain under 550 lbs.

6.2 Full Scale Roof Truss Testing

The roof truss structure is much more complicated as compared to the floor system and is shown in Figure 17. The roof truss system consists of a group of horizontal members and vertical members, with each being connected to another through pinned connection. The roof truss load testing was also conducted at Chengqi Tulou by means of a two point loading of up to 550 lbs. The load was applied onto a horizontal beam with the largest span while several vertical members were attached to this beam, which support roof beams. Figure 17 shows a photo of the major sections of the roof truss structure being evaluated while the entire roof truss structure is schematically illustrated where each member is assigned with a number (M1 to M14) and strain gage locations are indicated with reference to mounting member. More specifically, the load was applied onto Beam M10 between Columns M3 and M4.

The strain data generated from the roof truss structure testing are graphically shown in Figure 16b, as per the strain gage locations and corresponding structural members as defined in Figure 17. Similarly, the strain value was recorded as a function of loadings for each member mounted with strain gage. Each strain value at a given loading was an average of three measurements from three separate runs except that Member M4 (gage #8) had only two sets of data to average while the third set of data were mostly positive, resulting in uncertain trend for Member M4. It is not sure if this unclear trend was attributed to disturbance during testing or structural sensitivity. Note that the strain gages used were all 5 cm long gages to maximize the ability of detecting any small strains. All other members except M4 behaved as expected. The load applying member M10 (gage #4) gave a strain of 70 microstrain under maximal loading of 550 lbs. For M8, the bottom side was subjected to compression (negative strain) and the strain values were closely matching those of the top tension side.

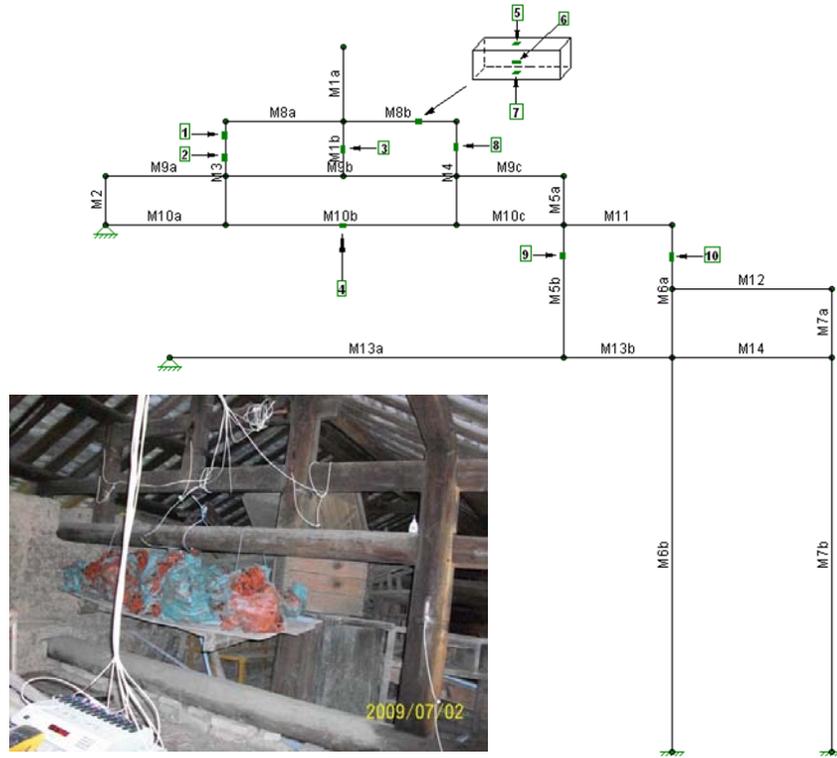


Fig 17: Load testing of Tulou roof truss, truss member definition and strain gage locations

6.3 Load Sharing Effects of Floor and Roof Truss Systems

The load testing of both the wooden floor and roof truss systems resulted in small strains in members with the max strain about 32 microstrain from the floor test and about 70 microstrain from the roof test at a loading of 550 lbs. The access space available limited to apply additional loads. Caution was applied not to generate disturbance while conducting test. Fortunately, strain responses from major loading members appeared to give meaningful trends. The results show that both the wooden roof truss and floor system are structurally sound even with the high age of the structure. From FE analysis (Stanislawski, 2011), for the floor system a modulus of elasticity of 1.85 msi would match the field test strain results well (i.e. 32 microstrain on the load applying member) while for the roof truss a modulus of elasticity of 0.85 msi would match the roof load test results closely (70 microstrain on the load applying member). The difference in stiffness between the roof truss and floor system could be a number of factors.

Although the floor system and roof system could be made out of different types of wood, it is more likely that they are created from the same source, in this case China-Fir. China-Fir exemplifies excellent structural strength with a modulus of elasticity around 2.0 msi as well as high decay resistance which also explains how the Tulou are able to maintain their structural strength over such a long period of years. This assumption was confirmed by Wang (2008) who states that China-Fir is used in the construction of the Hakka Tulou. Both the floor and roof systems are found to be structurally sound. Another observation that can be made on the roof truss is that the intermittent vertical members, specifically M3 and M4, intercept the longer horizontal member of M10. By doing so the moment has been dramatically reduced by cutting the effective length of the member. This shows that the Hakka people had good understanding of force distribution within the wooden roof structure as modern trusses are also similarly designed.

To further quantify how the floor and roof truss members respond to an external load and how the load is distributed among the neighboring members, one can further compare the strain data from each load testing with those from two extreme cases with well-defined boundary conditions: 1) as a simply supported beam with two equal concentrated loads symmetrically placed and 2) as a beam fixed at both ends, with two equal concentrated loads symmetrically placed. The computation gives that for the floor test, using $E = 1.85$ msi and at loading of 550 lbs, the maximal strain would be $68 \mu\epsilon$ for simple support beam and $17 \mu\epsilon$ for fixed beam; for the roof truss test, using $E = 0.85$ msi and also at 550 lbs, the maximal strain would be $311 \mu\epsilon$ for simple support beam and $101 \mu\epsilon$ for fixed beam (Stanislawski, 2011).

Therefore, one can argue that for the floor system load test, its loading scenario can be idealized through simple beam with fixed end model as opposed to a simple beam bending model. More specifically, with simple beam case being “0” moment at the supports and showing 68 microstrain, and fixed beam case being “100%” moment constraint at the supports and giving 17 microstrain, the structural redistribution of moment because of floor system will be a value of “71%” which is computed from field measurement value of 32 microstrain. This result demonstrates that the jointed neighboring members have a high load-sharing effect in a manner similar to a fixed beam. Similarly, for the roof truss load test, with simple beam case being “0” moment at the supports but resulting in 311 microstrain, and fixed beam case being “100%” moment constraint at the supports while yielding 101 microstrain, the field strain measurement further illustrates that the roof truss system being tested is providing extra stiffness, resulting in a microstrain of 70 only. This means that all the surrounding horizontal and vertical members connected to the load carrying beam, have acted in partial unison and restrained the load carrying beam such that the boundary conditions surpass those of a fixed beam.

7 THE WALL CRACK OF HUANJI TULO

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, 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 and this was discussed in Section 8.

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. 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 also 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 are used as inputs for FEA.

7.1 Has the Crack Self Healed?

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 18a. 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 18b. 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 18c, this crack was actually across the entire wall thickness and most surprisingly, there were no wall ribs at all inside the rammed earth wall.

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 (Stanislowski, 2011). A 3D model was built using the modulus of elasticity values reported in Table 2 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.

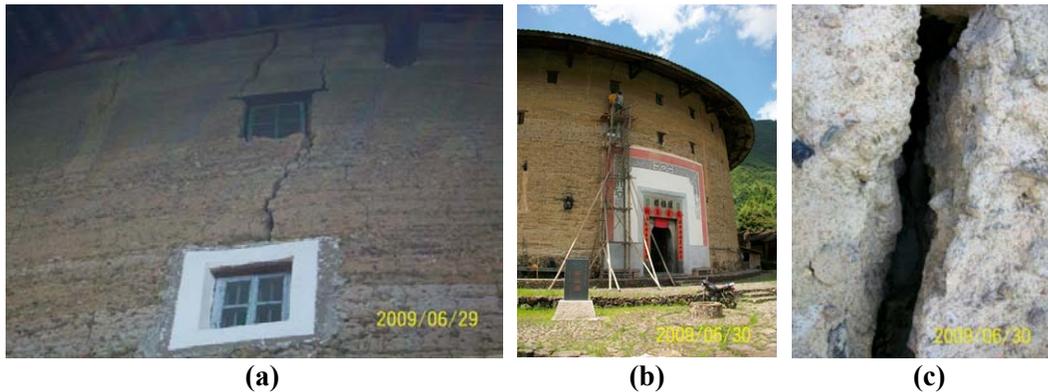


Figure 18: Huanji Tulou wall crack after earthquake, a) a global view of the crack, b) the crack location with reference to the ground and the access platform used during field study, c) close view of the crack

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 (Stanislowski, 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 Section 4. 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 19. 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 19: The crack and cavity at lintel end

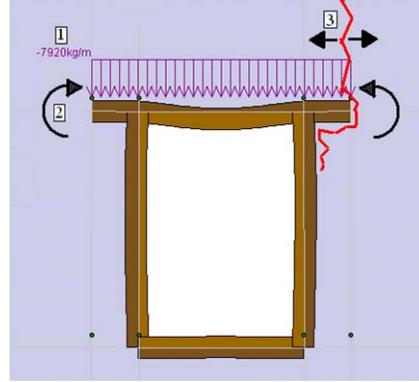


Figure 20: Lintel behavior

7.2 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 19) has been accurately modeled using FE analysis, based on Lintel behavior as shown in Figure 20 along with an earthquake load, using the material property data generated from this study (Table 2 and Table 3). Figure 21 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 (Stanislowski, 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 8.

8 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 FE modeling was conducted 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.

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).

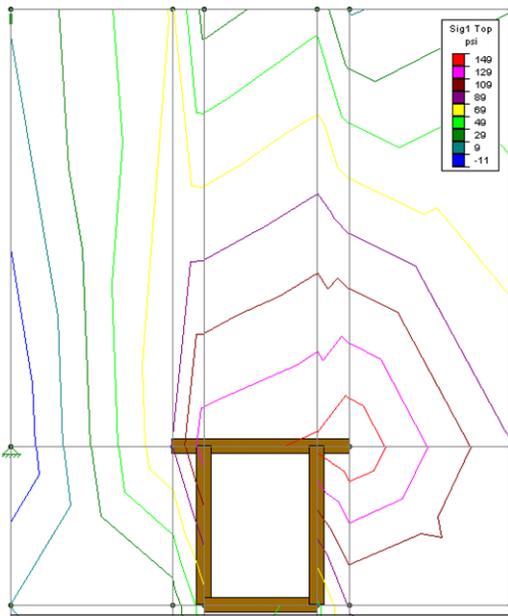


Figure 21: Stress in vertical direction due to horizontal load induced by Earthquake

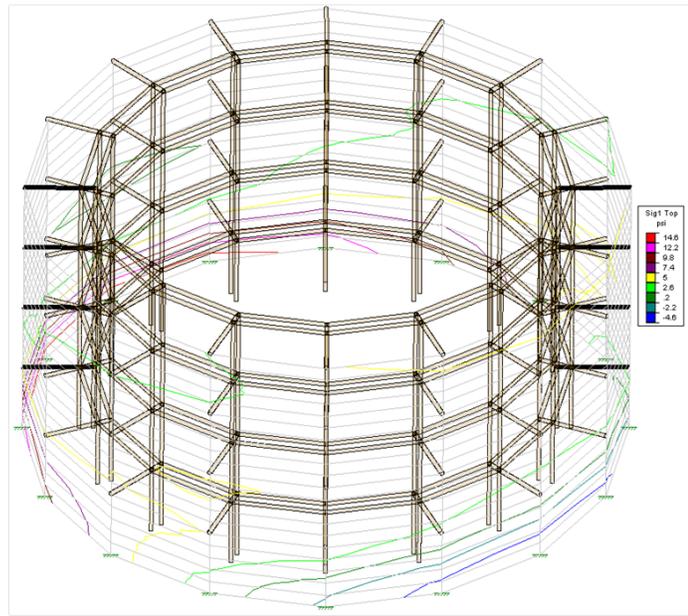


Fig 22: 3D Earthquake stress distribution of Huanji Tulou with inner wooden systems

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):

$$V = \frac{F S_{DS}}{R} W \quad (1)$$

$$S_{DS} = \frac{2}{3} F_a S_s \quad (2)$$

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/s². 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/s² 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:

$$V = .8W \quad (3)$$

Equation 3 calculates the base shear force for the entire structure. A density of 1600 kg/m³ 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 10⁶ kg (16.5 x 10⁶ lbs) which results in a total base shear of 5.99 x 10⁶ kg (13.2 x 10⁶ 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:

$$F_x = \frac{w_x}{W} V \quad (4)$$

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 x 10⁶ kg (3.3 x 10⁶ lbs) per floor. Divided 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 simultaneous 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 22, 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 coincidentally 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 2), 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.

9 CONCLUSIONS

Through this study we have investigated five in-service Hakka rammed earth structures, i.e. Fujian Tulou of China, in terms of their material and structural responses under thermal and mechanical loads. All field studies were conducted in a nondestructive manner using techniques such as infrared thermography, rebound hammer, ultrasonic testing, thermocouples, load tests on roof trusses and floors. The results show that NDE techniques such as ultrasonic and rebound hammer were proved effective to quantitatively compare the strength of rammed earth walls, while Infrared thermography was found not sensitive enough to detect the presence of wall ribs. The full scale load testing result and structural analyses conclude that both the floor and roof truss systems are structurally sound and the jointed neighboring members have a high load-sharing effect with the load-carrying beam.

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.

The Hakka people found ways to live in thermal comfort without the need of mechanical heating in winter or cooling in summer due to their effective use of rammed earth construction. This was done without the use of insulation, which would help better maintain heat within the structure during the winter seasons. Modern construction can simulate the Hakka construction techniques and make rammed earth construction a viable building material option of the future.

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