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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

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, we wish to investigate 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 in 2009, using nondestructive testing techniques such as infrared thermography, rebound hammer, ultrasonic testing, in-situ full scale load testing on roof truss and floor systems, and thermocouples for thermal data. During 2010, 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 of China. Finite element analyses were conducted to simulate those material and structural responses to arrive at better understanding.

More specifically, the campus studies conducted during year 2010 included the following: 1) Radiocarbon dating ages of Hakka Tulous 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 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 to examine the composition and morphology of the rammed earth samples from various Hakka Tulous; 4) Field data from nondestructive evaluation of rammed earth walls were reprocessed and compared with the strength and stiffness property data generated from laboratory materials testing; 5) Re-processing floor and roof systems load test data in comparison with finite element modeling results using RISA 2D program; 6) computer modeling of why and how the large crack of Huanji Tulou was formed under an earthquake load 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.

Findings:

Hakka Tulous are rammed earth structures that have survived the material aging and natural weathering for over 1000 years. The objectives of this study are 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 'breath' 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 report.

Training and Development:

One graduate student of US origin, Daniel Stanislawski, Civil and Environmental Engineering at WVU, has been employed as a graduate research assistant since January 1, 2010. Daniel has 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 contacts our China partner from time to time for information exchange. He is planning to complete his thesis, entitled 'Mechanical Response and Finite Element Modeling of Hakka Tulou Rammed Earth Structures' and graduate in May 2011. During the course of this study, Daniel has been extensively exposed to Hakka Tulou architecture and associated Hakka culture. It should be 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 History Made for Tomorrow film produced by US History Channel/AETN, featuring part of our work was shown within WVU-Civil and Environmental Engineering Department and Chemical Engineering Department in December 2010.

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

Web/Internet Site

URL(s):

http://www2.cemr.wvu.edu/~rliang/hakkatulou.html

Description:

The PIs are developing a website to help disseminate our 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 shown at different conferences and public events whenever appropriate.

Contributions

Contributions within Discipline:

1. Establish protocol for NDE of historic buildings including carbon dating for age measurement
2. Develop approaches to model structural responses under thermal, mecahnical and earthquake loads

Contributions to Other Disciplines:

Contributions to Human Resource Development:

One American graduate student has been working on the project since Jan 1, 2010. This has 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. We have been planning Hakka Tulou Forum 2011: Structures of Sustainability will take place on Oct 28-30, 2011, Xiamen, China.

Contributions Beyond Science and Engineering:

Conference Proceedings

Special Requirements

Special reporting requirements: None

Change in Objectives or Scope: None

Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Organizational Partners

Any Journal

Contributions: To Any Other Disciplines

Contributions: To Any Beyond Science and Engineering

Any Conference

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Annual Report 2010

Thermal and Mechanical Responses of Historic Hakka Tulou Rammed Earth Structures: Lessons to Be Learned for a Sustainable Future

Prepared by:

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December 30, 2010

Thermal and Mechanical Responses of Historic Hakka Tulou Rammed Earth Structures: Lessons to Be Learned for a Sustainable Future

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Constructed Facilities Center, West Virginia University, Morgantown, WV 26506

Abstract

Hakka Tulous are rammed earth structures that have survived the effects of material aging and natural weathering for over one thousand years. The key building material, rammed earth in Hakka Tulou structures has provided structural stability along with thermal comfort to the respective inhabitants of the Hakka Tulous. Through material testing and structural analysis, this study has examined the durability, structural integrity and living comfort of rammed earth construction in the Hakka Tulous. The sustainability concepts embedded in Hakka Tulous have been highlighted in terms of their design, construction, operation, and maintenance for future green structures.

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 [1]. Many historic rammed earth structures are either in service or abandoned, in many countries, e.g., China, India, Spain, Morocco, Yemen, Egypt [2-4]. 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 [5]. 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.

Figure 1: Hakka Tulou Village, Chuxi Tulou Group, Yongding, Fujian, China

Figure 2: Location Map of Fujian Tulou in China

The in-service World Heritage Hakka Tulous, in the Fujian Province of China, are unique in design and performance and are historic because of their service ranging from 100 to 1300 years [6]. An image of a Tulou village is presented in Figure 1 and Figure 2 shows geographic location map of Fujian Tulous in China. Hakka Tulou rammed earth buildings have thick (~2 m) outer rammed earth walls and inner wooden structures making up floors and rooms. Those buildings are three to five stories in height, and circular or square in shape, 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 Tulous' characteristics, architecture including defense devices and fire walls, and construction techniques [7-9]. It is worth noting that Aaberg, a Danish architect, visited Hakka earth buildings in 1997 and reported the architecture marvel of these structures [10]. More recently, Ostrowski, a Canadian architect has been researching ecological footprint of Hakka earth buildings [11].

Hakka Tulou rammed earth buildings reflect the emergence of innovation, evolution, and advancement in the engineering of rammed earth construction from the 8th to 20th centuries. They can be considered "green" in terms of their planning, design, construction, lifestyle, resource management, renewable energy, and modest ecological footprint [11]. However, people have underestimated the engineering value and historical significance of those buildings in terms of energy consumption for comfortable living, sustainability, and durability.

Engineers at West Virginia University Constructed Facilities Center in collaboration with members from School of Architecture and Civil Engineering, Xiamen University, China and ASH-Autonomous & Sustainable Housing Inc, Canada traveled to Yongding County, Fujian, China from June 15 - July 15, 2009 and performed field studies on the material and structural responses of the historic Hakka Tulous. A group photo of the research team with local Government Officials is shown in Figure 3.

Figure 3: The Research Team Standing in the Front of Zhencheng Tulou, Hongkeng Village, Yongding, Fujian. L to R: Zhaoting Zhang, Jorg Ostrowski, Ruifeng Liang, Gangarao Hota, Ying Lei, Yuan Lee, Helen Ostrowski, Meiqun Lu

The objective of this study is 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 modeling. The scope of work includes: 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. The specific activities conducted are illustrated in form of a chart shown in Figure 4.

All field studies were conducted in a nondestructive 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 study were then further processed at West Virginia University (WVU) and Xiamen University (XMU) for their implications along with the data generated thru testing the field-collected samples at both WVU and XMU laboratories, including carbon dating. A list of Hakka Tulous studied is shown in Table 1 [12].

Table 1: Hakka Tulou 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
Zhencheng Tulou	Round	4 story	about 100 years	in service

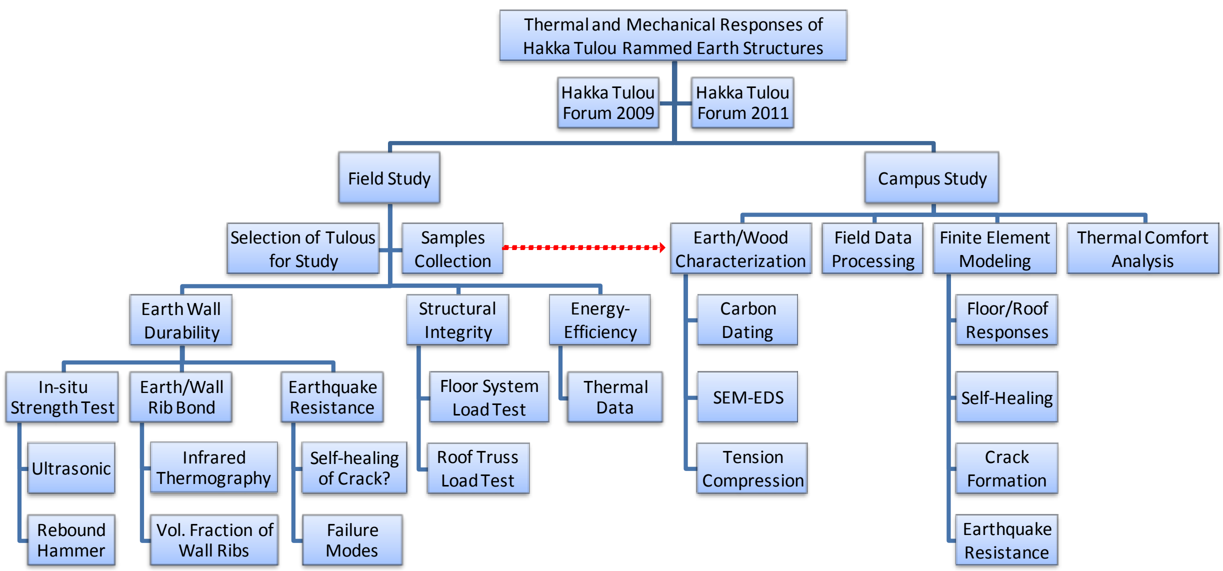


Figure 4: The Scope of Work Conducted

* Hakka Tulou Forum 2009: Lessons to Be Learned, Past, Present and Future, June 24, 2009, Xiamen, China
Hakka Tulou Forum 2011: Structures of Sustainability, October 28-30, 2011, Xiamen, China

2. Radiocarbon Dating Ages of Hakka Tulous

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 5. 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.

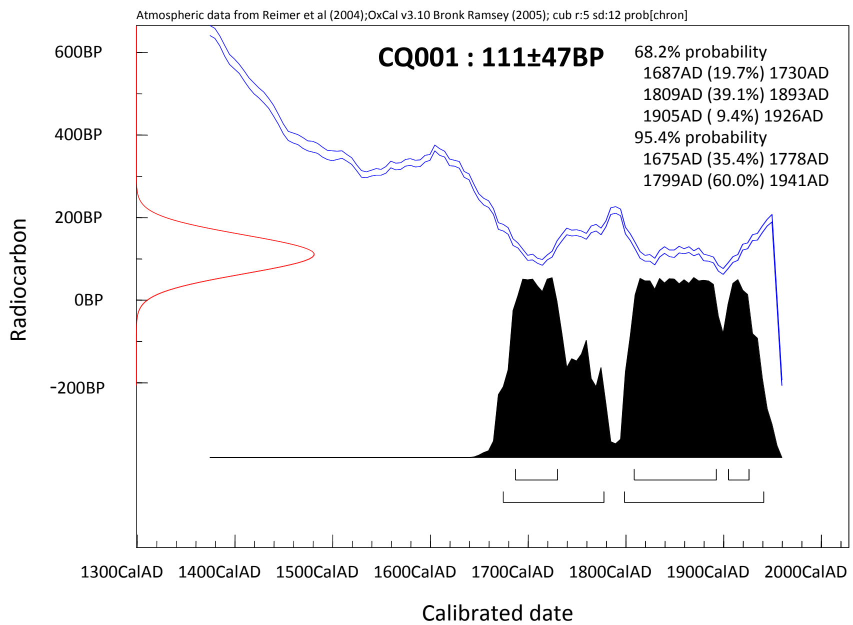


Figure 5: Carbon Dating Age of Chengqi Tulou

3. Material Characterization

In order to analyze and model the structural responses of Hakka Tulous, 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 some Tulous' walls for increased strength, were collected from the Tulous that were field–studied during June 15-July 15, 2009. It should be noted that strength tests under tension and compression were performed on the acquired samples keeping in mind that the sizes of the samples were not in accordance with the specimen requirements of ASTM standards, due to crumbling nature while extracting the samples from the existing historic structures or preparing the specimens at laboratories from those field-samples. As a matter of fact, core extracts as per ASTM standard of the rammed earth walls from the Tulous were tried in field but not successful due to the rammed earth becoming brittle under the vibrations caused by the extracting equipment [12].

Some material mechanical tests were performed by Xiamen University in China and data from the tests were then sent to West Virginia University for further analysis and integration. Other materials tests and data analyses were performed entirely at West Virginia University Constructed Facilities Center. From those static tests stress-strain curves were generated for each sample from which the modulus of elasticity was determined and used in modeling. Small pieces of earth samples were also viewed on an advanced Scanning Electron Microscopy (SEM) for morphology and further tested on Energy-dispersive X-ray Spectroscopy (EDS) for the sample's elemental analysis (chemical characterization).

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 Tulous, 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 6 shows the images for Fuxing Tulou and Chengqi Tulou earth samples, respectively, in a scale of 5 micrometer.

After reviewing the SEM images of the earth samples from five Tulous it can be seen that each of the rammed earth samples looks fairly consistent from one viewing area to another. Except Fuxing Tulou earth, which is over 1200 years old, has porous network type morphology (Figure 6: Left), while all others (Zhencheng, Chengqi, Wuyun, and Huanji Tulous) have mica-like flake surface structures (Figure 6: Right). Chengqi and Wuyun Tulou earth samples have shown presence of wood fibers that were well bonded with surrounding earth (Shown in Figure 7) while Fuxing and Zhencheng Tulou earth samples are mixed with stone/rocks. It appears the morphological observations alone are not sufficient to directly explain the difference in earth property among those Tulou samples. However, Zhencheng samples have lots of smaller uniform 'rocks' in the sample. This could attribute to the fact that the Zhencheng Tulou, at the youngest age of 100 years, has the best quality material due to quality of preparing rammed earth, as proven by nondestructive testing data whose details are given in Section 4**.**

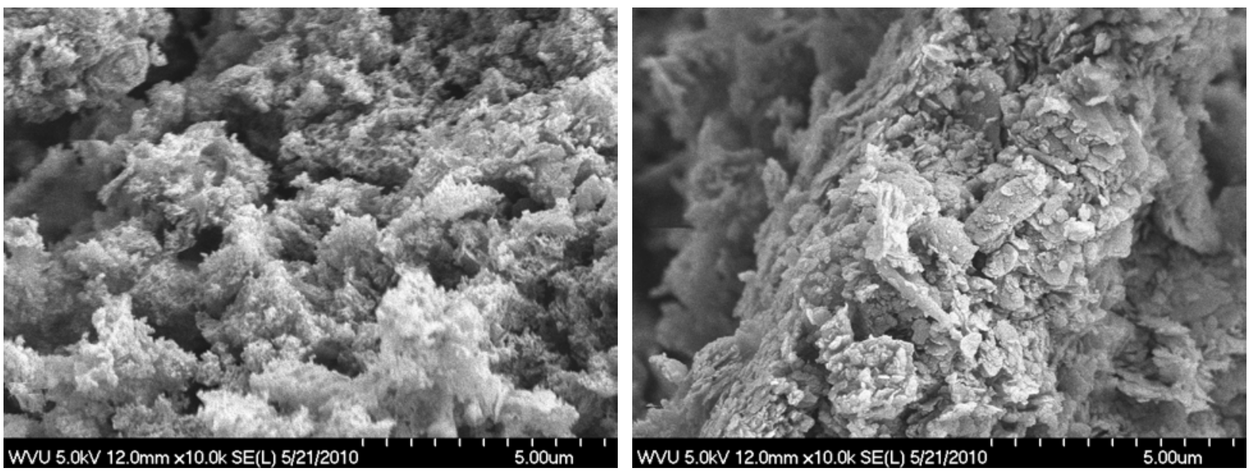


Figure 6: Fuxing Tulou (Left) and Chengqi Tulou (Right) Earth Sample SEM Images

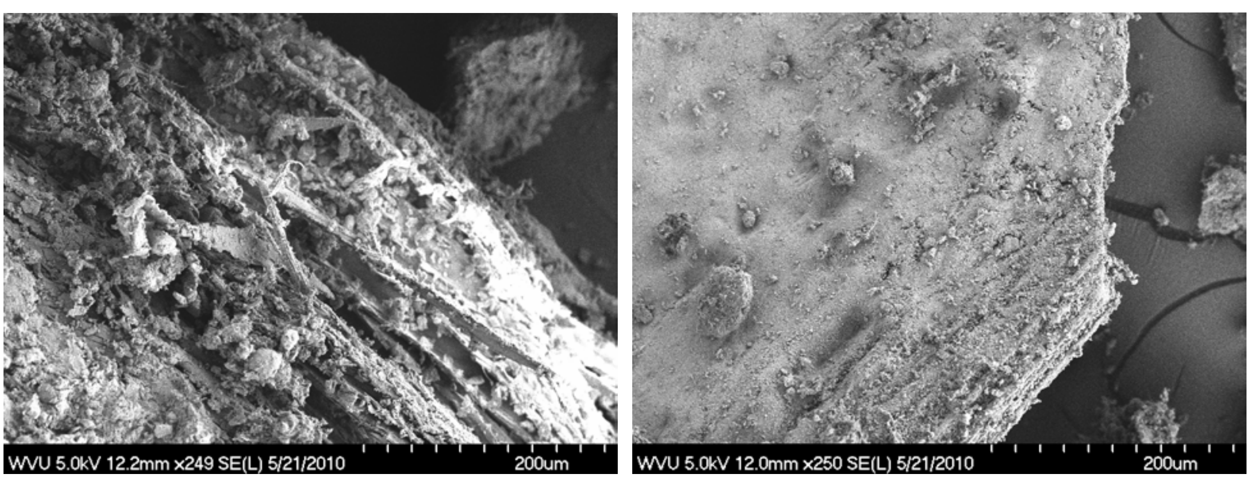


Figure 7: Wuyun Tulou (Left) and Chengqi Tulou (Right) Earth Sample SEM Image Showing Wood Fibers

EDS analysis can explain 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 8 (Left) and EDS only for Fuxing Tulou is in Figure 8 (Right). For Wuyun Tulou and Chengqi Tulou samples where there embedded wooden ribs as reflected in micrographs shown in Figure 7, their EDS charts have strong Carbon peaks. Chengqi Tulou earth sample without wood EDS chart is compared with those of Chengqi and Wuyun Tulou earth with wood in the viewing area and are presented in Figure 9. A comparison in chemical composition among five Tulous earth samples is listed in Table 2.

Table 2: Chemical Compositions of Tulou Earth Samples Revealed by EDS

Title of Tulou	Dominant Elements	Less Dominant Elements
Fuxing Tulou	O, Al, Si, Ca	C, Fe, Na, Mg, P, Cl, K
Wuyun Tulou	Ti, O, Al, Si	C, Fe, Na, Mg, Cl, K, Ca
Chengqi Tulou	C, Ti, O, Al, Si	Fe, Mg, K, Ca
Huanji Tulou	O, Al, Si	C, Fe, Na, Mg, K
Zhencheng Tulou	Ti, O, Al, Si	C, Fe, Na, Mg, P, K

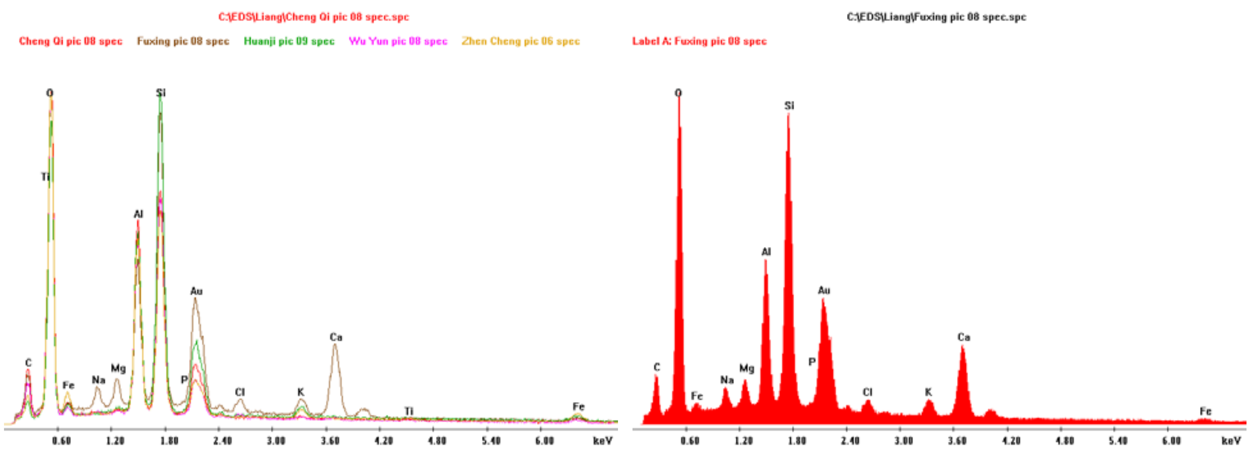


Figure 8: 5 Tulous Studied Overlay EDS (Left) and Fuxing Tulou (Right) Earth Sample EDS Charts

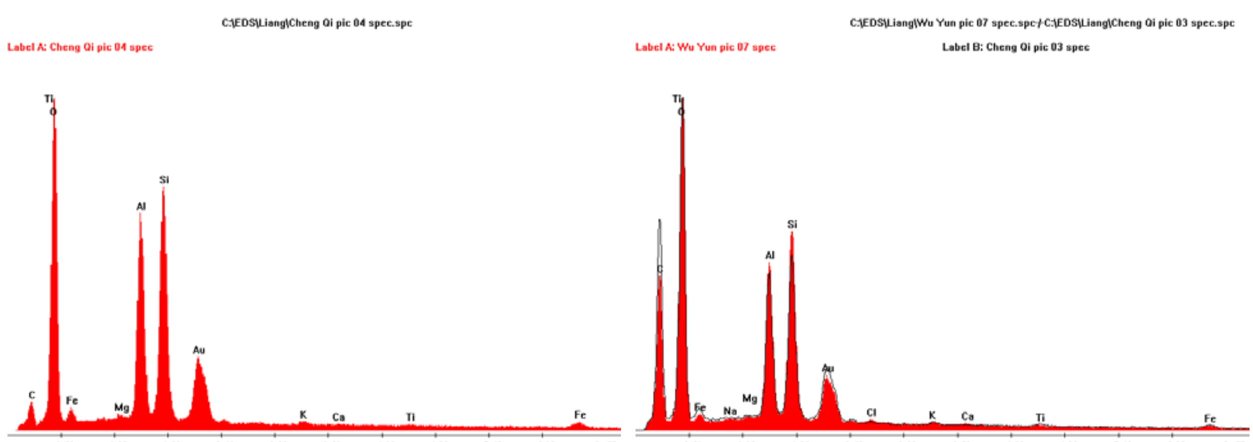


Figure 9: Chengqi Earth without Wood (Left) versus Chengqi and Wuyun Earth with Wood (Right) EDS

From the EDS data one can see that all the samples from the five different Tulous 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 Tulous, 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.

It should be noted that the oldest Tulou, Fuxing Tulou, displays different spectrum from remaining four Tulous 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. It should also be noted that as discussed in Section 6 where we argue if Huanji Tulou's 20 cm crack were able to self-heal or not, calcium is the key element responsible for the possible autogenous healing process of microcracks. However, based on the EDS data no calcium was found in the earth sample of the Huanji Tulou (Figure 8: Left).

3.2 Compression Properties of Rammed Earth

Rammed earth samples from the main wall structures of five Tulous were extracted and tested. Figure 10 shows representatively Chengqi Tulou earth sample before and after testing, while the resulting stress/strain curve is shown in Figure 11. Table 3 summarizes the results of the rammed earth compression tests performed by both WVU and Xiamen University. Note that testing of Huanji Tulou earth samples did not result in reliable property data.

Figure 10: Chengqi Earth Sample before and after Testing at WVU

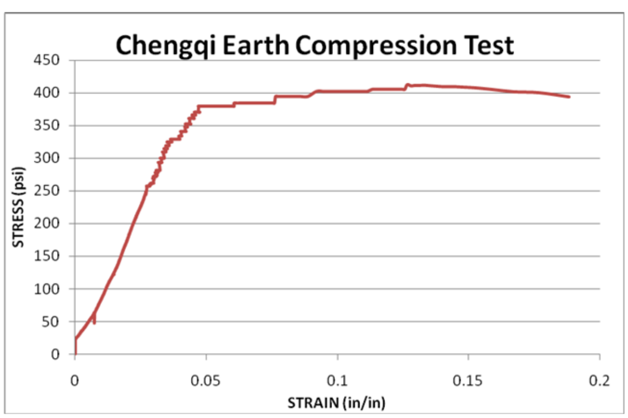


Figure 11: Chengqi Tulou Earth Stress/Strain Curve under Compression

Table 3: 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

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 [11, 13]. 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.

Data from testing at West Virginia University on the Wuyun earth samples correlate closely to the Xiamen University's findings with regard to the modulus of elasticity, however not as closely for the ultimate strength. A modulus of elasticity of 2129 psi and ultimate strength of 279 psi were found for the Wuyun earth sample at WVU. These rammed earth property values are all consistent with the values of soft clay which has a modulus of elasticity range of 700 psi to 2800 psi [14].

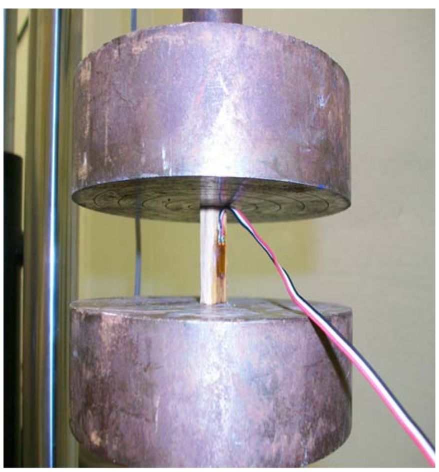
The newer Zhencheng and Chengqi Tulous which have an age of 100 and 300 years respectively are much stiffer and thus have higher average values for their moduli of elasticity than Wuyun Tulou's. West Virginia University testing found the Chengqi sample having a modulus of elasticity of 8147 psi and ultimate strength of 411 psi whereas the Zhencheng sample was found to have a modulus of elasticity of 4291 psi and an ultimate strength of 126 psi. The Xiamen University meanwhile found the Zhencheng earth samples to yield a modulus of elasticity of 3598 psi and ultimate strength of 196psi, in agreement with WVU's data. Note that as revealed by SEM, Chengqi Tulou earth sample has wood fiber reinforcement while Zhencheng Tulou earth sample has plenty of small rocks. These help explain their higher stiffness than the above referred regular soft soil, instead, approaching the values for sandy clays clay shales, and silty sand [14].

Again, as shown in Table 3, 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 Tulous. On contrast, the rammed earth sample from Wuyun Tulou at 500 years in-service, has the lowest strength and stiffness, 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.

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 (Figure 12) or inside an eroded rammed earth wall (see later Figure 21). 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 (Figure 13) and typical stress/strain curves are shown in Figure 14. Table 4 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 Tulous.

Figure 12: Rough Rammed Earth Walls of Chengqi Tulou Showing Layer Construction and Wall Ribs



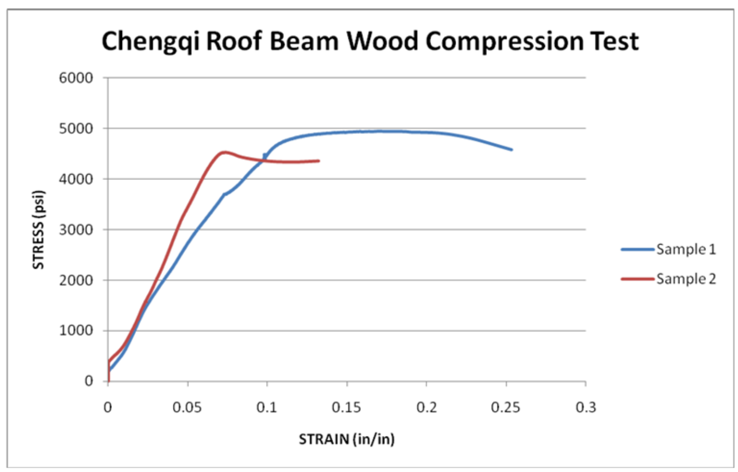


Figure 13: Chengqi Tulou Wall Rib Sample Being Tested under Compression at WVU

Figure 14: Chengqi Roof Beam Wood Sample Stress/Strain Curve

Wooden wall rib samples from Chengqi Tulou, tested by the Xiamen University in China, behaved fairly similarly under both compression and tension. In compression, the average modulus of elasticity for the wooden samples is 46799 psi while in tension, the average modulus of elasticity for the same wood sample is 34737 psi. These data are in line with the modulus value of 57308psi that is generated by WVU. These values are much lower than those from any typical wood whose modulus of elasticity is usually in the magnitudes of hundred thousand's of psi and higher [15]. The lower modulus of elasticity for the sample tested could be due to aging of the samples, as well as being damaged as they had been pultruding from an existing rammed earth wall. Also, the size of the samples tested may have altered the results as well.

Another piece of wooden wall rib from Chengqi Tulou and the wall rib sample from Fuxing Tulou, tested by West Virginia University, showed much higher strength in compression as well as more consistent data with an average modulus of elasticity of 303364 psi and 227944 psi and an average ultimate strength of 4870 psi and 4376 psi, respectively. A piece of wood that was delaminated from a structural beam which makes up different parts of the wooden roof truss at the Chengqi Tulou, was also tested, and resulted in an average modulus of elasticity of 175461psi. Lastly, bark samples that act as wall rib reinforcement at the Chengqi Tulou were also tested and resulted in an average modulus of elasticity of 52583 psi and an average ultimate strength of 2484 psi. It is interesting to note that the stiffness of all the samples tested at West Virginia University, including the bark, was higher than that generated by the Xiamen University in China.

Table 4: 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

Bamboo samples were tested both in tension by the Xiamen University and in compression by West Virginia University. In tension, bamboo showed an average modulus of elasticity of 463178 psi and an ultimate strength of 4452 psi. In compression, bamboo showed an average modulus of elasticity of 300023 psi and an ultimate strength of 11039 psi. Even though this modulus is much higher than wood it is still much lower than that of the typical average modulus of elasticity of tension for bamboo which is about 2.76 msi [16]. Similar to the wood samples, the lower modulus of elasticity for the bamboo samples tested could be due to the age of the samples, representing degradation of the bamboo through aging since they were collected by cutting the pultruding section from the wall (Figure 23). The non-standard size of the samples tested may have also altered the results.

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. More specifically, using the above material property data for the rammed earth, wood, and bamboo, one can use the Rule of Mixtures to find the modulus of elasticity of the reinforced rammed earth wall for modeling purposes.

4. Non-Destructive Evaluation of Rammed Earth Walls

Nondestructive testing (NDT) techniques refer to those techniques or methods that enable the testing of materials/ structural components without impairing their future usefulness. Those are the only class of techniques that can be used for testing and long-term monitoring of in-situ structures [17]. Because of the nature of the present study, nondestructive testing was necessary as to be able to understand the condition of the material and rammed earth walls, without destroying 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 structural integrity of several Tulou structures in a comparative manner. In addition, Infrared Thermograpgy 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 8.

4.1 Ultrasonic Method

Ultrasonic testing is a NDT 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 walls of the Tulou structures and be detected by a receiver (as shown in Figure 15). 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 [18].

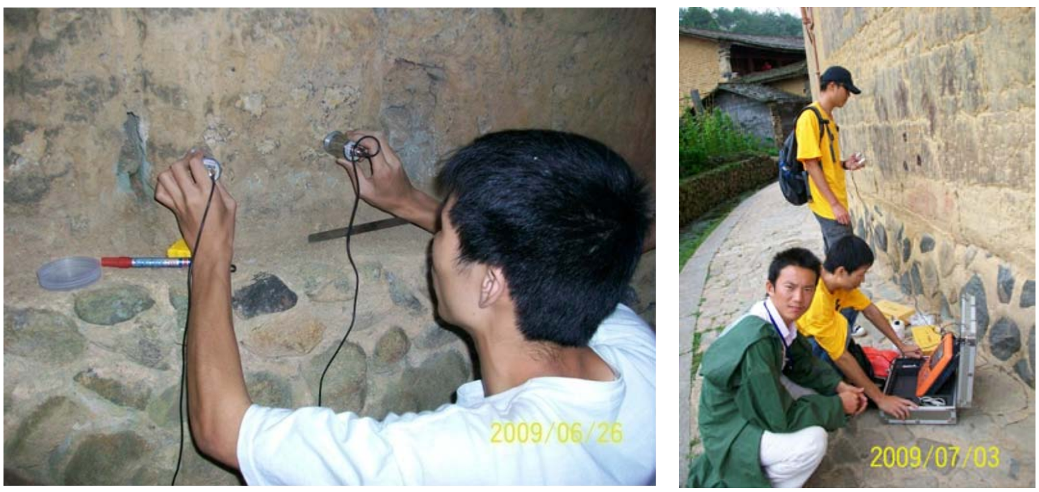
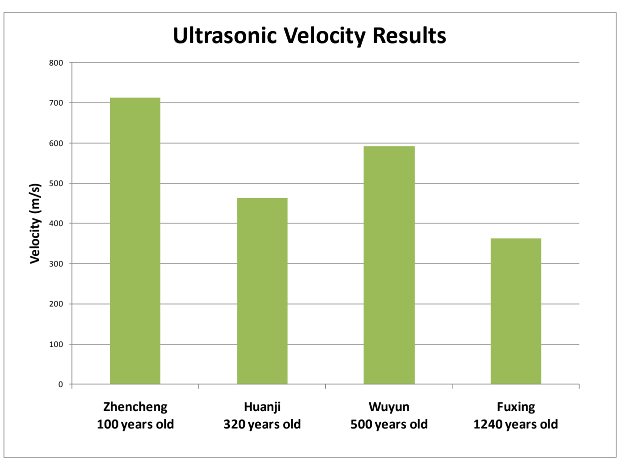


Figure 15: Ultrasonic Testing Heads and Device



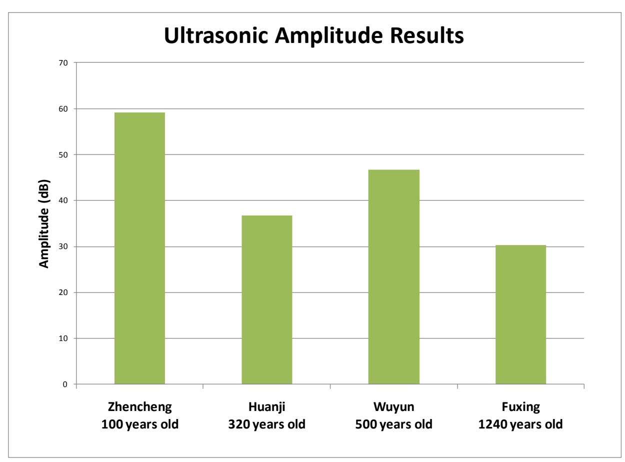


Figure 16: Ultrasonic Velocity Results **Figure 17:** Ultrasonic Amplitude Results

*Fuxing Tulou data obtained on wet walls due to rain

Figures 16 and 17 show the ultrasonic velocity and amplitude results for the Tulous 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 Figure 16, apparently, there is not direct correlation between the age of the Tulou structures and the velocity of the ultrasonic wave (the strength of the rammed earth walls). 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.

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

4.2 Rebound Hammer Method

As per ASTM C 805, "Standard Test Method for Rebound Number of Hardened Concrete", 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 18. For the rebound hammer tests during field study, two types of rebound hammers were used, one specifically for brick and another specifically for mortar. Figure 19 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.

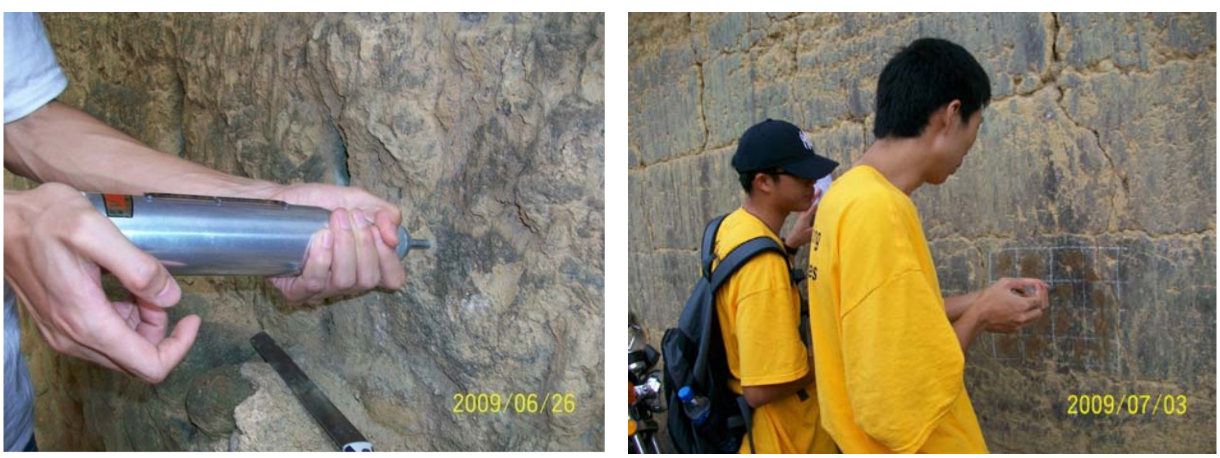


Figure 18: Rebound Hammer and Testing Point Pattern

Each data point represents an average of 32 to 64 readings in case of rebound hammer measurement. Also, all the measurements from Fuxing Tulou were conducted on wet walls because of raining weather during field study and the earth wall might have become soft. 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 shown in Section 3.

As shown in Figure 19, 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 Tulou would have the highest modulus of the elasticity, followed by Fuxing Tulou, and the Wuyun Tulou and Huanji Tulou would have similar low modulus values. Except for Huanji Tulou where the mortar rebound hammer average reading was much higher than the brick rebound hammer, for other Tulous, the brick rebound hammer always gave higher average reading than the mortar rebound hammer. Note that each of these values is a statistical average over a number of measurements.

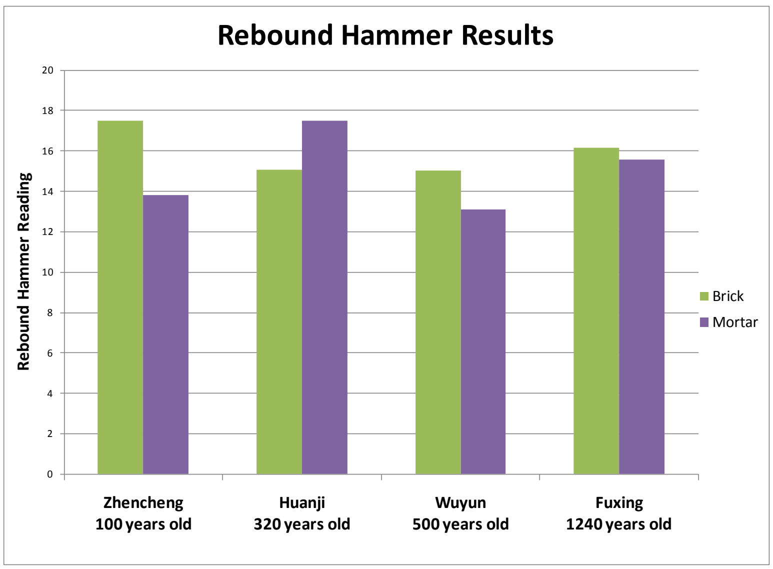


Figure 19: Rebound Hammer Results
*Fuxing Tulou data obtained on wet walls due to rain

For the purpose of this project, nondestructive testing using ultrasonic or rebound hammer can effectively tell us a quantitative comparison of the strength of rammed earth walls between the different Tulous 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 as described in Section 3. Instead, a comparison of NDT data with experimentally determined strength data of the rammed earth walls, as illustrated in the section, would establish the confidence for further wide use of such NDT techniques.

The data from the above NDT tests 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 local composition of the rammed earth and reinforcement from bamboo to sticks also has a serious impact on the strength of the rammed earth wall. 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 Thermalgraphy Scanning Method

Infrared thermography (IRT) is a viable non-destructive evaluation 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 20) and brought to China for field studies.

Figure 19: Portable Handheld IRT Camera Used

Figure 21: Eroded Rammed Earth Wall of a Tulou Exposing Wooden Chips Inside [19].

IRT camera was intended to perform a couple of functions upon verification of its usefulness during field study. One function would be explored if it could be used 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. A clear view of wall ribs inside a wall is shown in Figure 21.

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). However, the IRT is indeed able to detect the wall rib as shown in Figure 22 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.

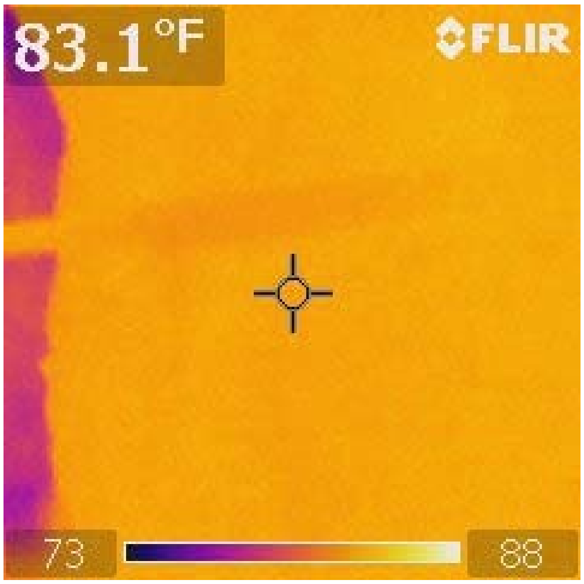


Figure 22: IRT Detecting Shallow Wall Rib

Figure 23: Bamboo Strips as Wall Ribs

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 Section 6 in more details. 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. We assumed that the wall was reinforced with wall ribs. We further proposed to use the IRT technique to scan the cracking 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 recovered. Unfortunately it was found by the team 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.

Estimating Volume of Reinforcement (Wall Ribs) in Rammed Earth Wall Construction

To estimate the volume of reinforcement in a typical rammed wall, instead of using IRT scanning camera, a cross section of rammed earth wall was identified with pultruding bamboo wall ribs and shown in Figure 23. 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 Tulous.

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 .5 inch x 1 inch, which results in a fiber cross section area of .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 23, then the volume fraction for wood reinforcement comes out to be 6.7% and the volume fraction for bamboo reinforcement to be 1.8%.

As discussed in Section 3, the most conservative modulus of elasticity for wooden wall ribs is in tension and is found to be 34737 psi while the modulus of elasticity of bamboo in tension is found to be 463178 psi. For modeling purposes and in order to be conservative, the modulus of elasticity used to represent the rammed earth is 1706 psi of the Wuyun Tulou earth sample. Hence, the modulus of elasticity for the rammed earth wall with wall ribs can be calculated as per the Rule of Mixture, using the above volume fraction of reinforcement.

5. Structural Evaluation of Floor and Roof Systems though Load Tests and Computer Modeling

When discussing the structural integrity of Hakka Tulous, attention must be turned to the inner wooden structure of the Tulou. The inner wooden structure of the Tulou carries the loads that are experienced within the Tulou, as well as external loads such as wind loads, and distributes these loads to both the rammed earth walls and the interior wooden columns. Figure 24 displays a cross section of a typical Tulou which shows how the wooden structure integrates into the thick rammed earth walls.

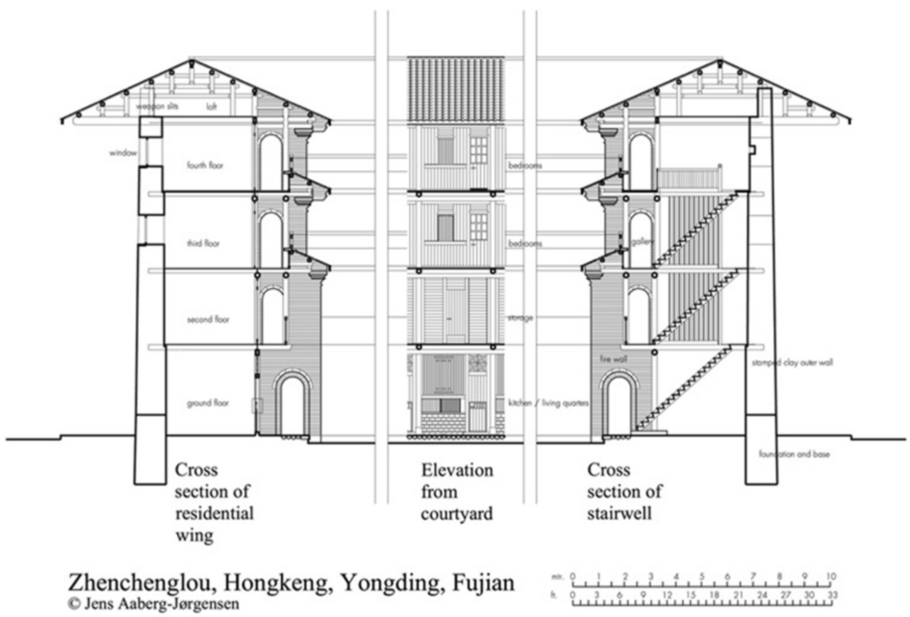


Figure 24: Cross Section of a Typical Tulou [20]

5.1 Full Scale Floor System Testing and Analysis

The floor system of a Tulou building consists of a number of columns, beams and floor panels (Figure 25). Each load carrying member is jointed to each other thru 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. 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.

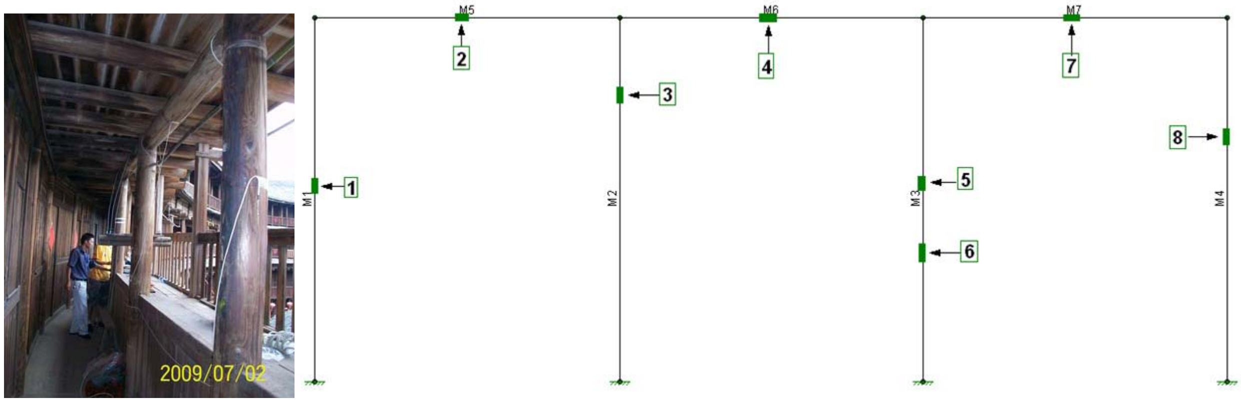


Figure 25: Load Testing of Floor System, Member Definition and Strain Gage Locations

Table 5: Floor Test Strain Data and Model Predictions

	Member	M1	M2	M3	M4	M5	M6	M7
	Gauge #:	1	3	5	8	2	4	7
	Load, lbs	με	με	με	με	με	με	με
Field Test Data	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	110	0.67	-3.00	-6.50	-1.33	-1.33	4.67	-2.67
	220	-2.00	-5.50	-17.75	-4.00	-2.33	11.33	-3.00
	330	-4.33	-9.50	-30.33	-5.33	-4.33	19.33	-3.67
	440	-2.50	-12.50	-39.00	-3.00	-5.00	27.50	-2.00
	550	-5.50	-13.50	-48.00	-4.00	-7.00	32.00	-1.00
Risa, E=2 msi	550	0.20	-2.99	-2.63	0.24	-6.78	29.69	-6.26
Risa, E=1.5 msi	550	0.27	-3.99	-3.50	0.32	-9.05	39.58	-8.34

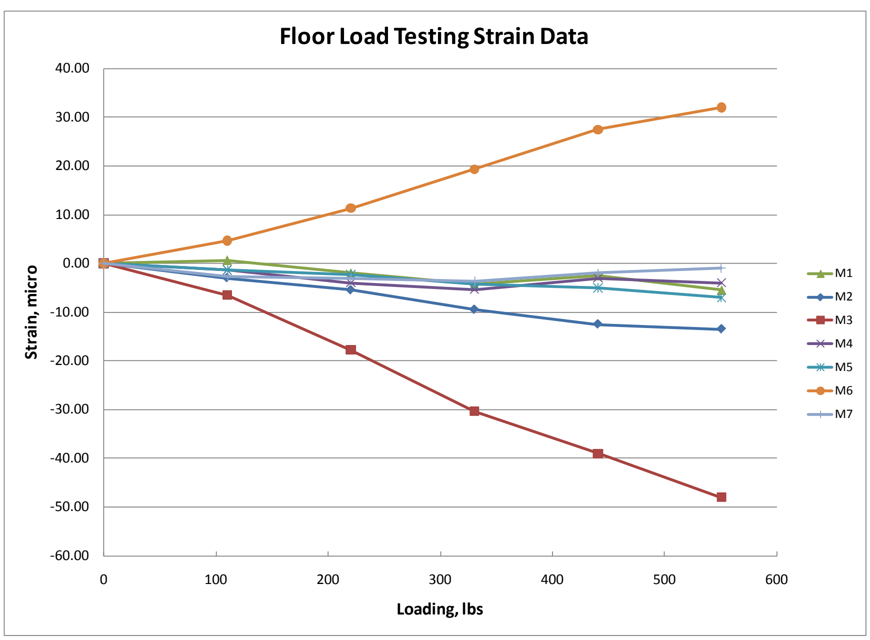


Figure 26: Tulou Floor System Member Strain Data

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 Figures 25 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 a form of nondestructive testing that allows us to predict or estimate the material properties of a structure without damage to the structure itself. Also, load testing of such structures shows how structurally sound a structure may or may not be. In order to predict structural properties of a structure, one can compare the strain gage data from the load test to the strain/stress values from an FE model. One may back calculate and predict the modulus of elasticity of a material in the FE model by matching the strain from the FE model to the strain values from the load tests. It is important to note that FE models do not perfectly match actual conditions and thus these results should be taken as an estimate of the actual values. In this study, RISA 2D software was employed to model the responses of the floor and roof systems.

The strain data generated from the floor testing are listed in Table 5 and graphically shown in Figure 26, in terms of the strain gage locations and corresponding structural members as defined in Figure 25. 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 two sets of model predictions for each member at a loading of 550 lbs were also listed in Table 5 and compared with experimental values.

5.2 Full Scale Roof Truss Testing and Analysis

The roof truss structure is much more complicated as compared to the floor system and is shown in Figure 27. 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 27 shows the major sections of the roof truss structure being evaluated while the entire roof truss structure is schematically illustrated in Figure 28 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 loaded onto Beam M10 between Columns M3 and M4.

Figure 27: Load Testing of Roof Truss

The strain data generated from the roof truss structure testing are listed in Table 6 and graphically shown in Figure 29, as per the strain gage locations and corresponding structural members as defined in Figure 28.

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 had only two sets of data to average while the 3rd 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. The two sets of model predictions for each member being monitored at a loading of 550 lbs were also listed in Table 6 and compared with experimental values.

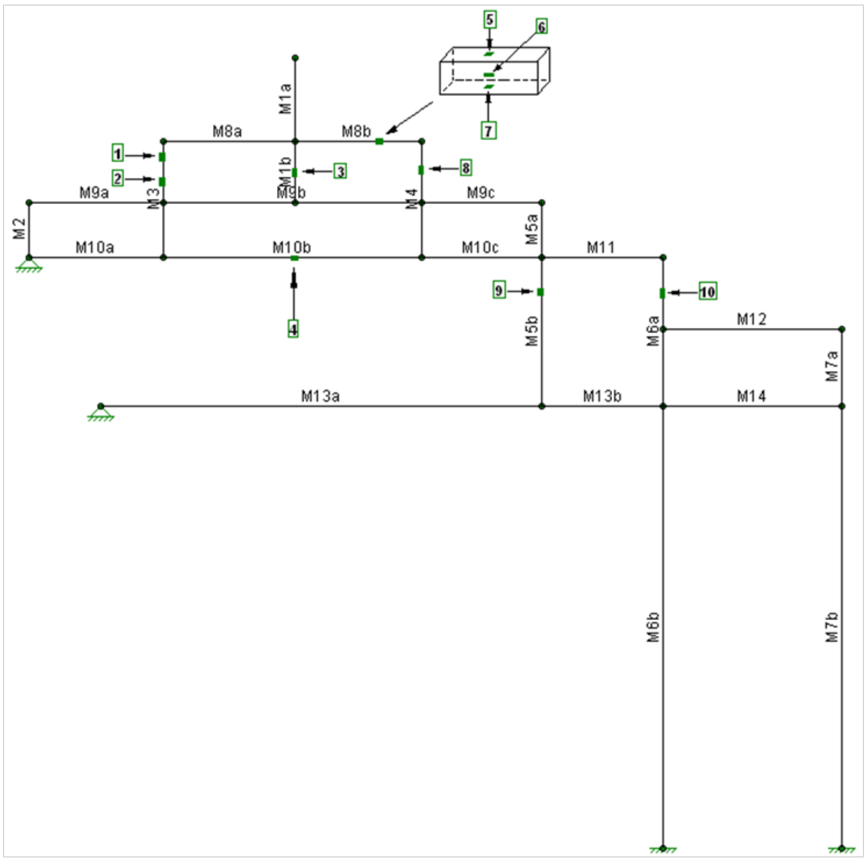


Figure 28: Tulou Roof Truss Member Definition and Strain Gage Locations

Table 6: Roof System Load Test Strain Data and Model Predictions

	Member	M1	M3	M4	M5	M6	M8 Top	M8 Bottom	M10
	Gauge #:	3	1	8	9	10	5	7	4
	Load, lbs	με	με	με	με	με	με	με	με
Field Test Data	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	55	-0.50	0.00	-1.00	-0.50	0.40	2.00	-2.33	5.00
	110	3.00	0.83	-1.00	-0.60	0.00	8.00	-6.25	12.00
	165	6.00	0.75	1.50	-1.00	-0.60	9.00	-10.33	21.00
	220	5.00	-0.67	-2.00	-1.00	-0.50	10.00	-15.00	27.00
	275	5.50	-0.75	0.00	-2.00	-0.60	13.00	-16.67	33.00
	330	6.33	-0.67	2.00	-1.50	-0.33	15.00	-21.25	40.33
	385	6.00	-0.50	3.50	-1.67	-0.20	17.00	-23.00	48.50
	440	5.67	-0.67	-7.00	-2.00	1.60	19.00	-26.67	54.67
	495	4.50	0.00	0.00	-0.33	-0.50	21.00	-28.00	63.50
	550	5.33	0.67	-3.50	-1.25	1.00	23.00	-28.67	69.67
Risa, E=1 msi	550	0.48	-0.12	-0.18	-1.05	-6.02	6.82	-15.22	59.53
Risa, E=0.75 msi	550	0.65	-0.16	-0.24	-1.40	-8.03	9.09	-20.29	79.37

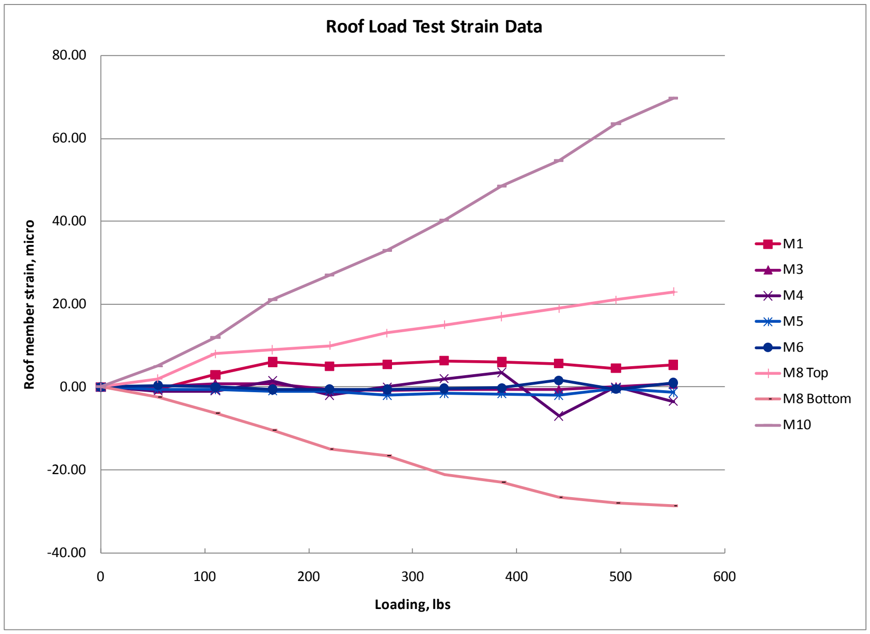


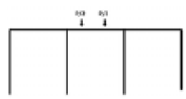
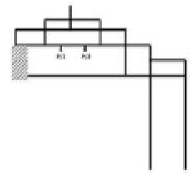
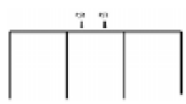
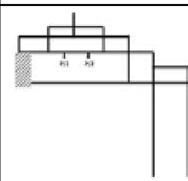
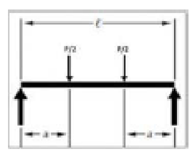
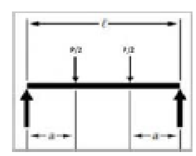
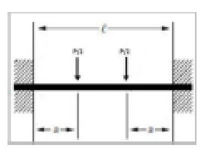
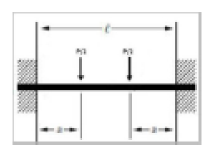
Figure 29: Tulou Roof Truss Member Strain Data

5.3 Load Sharing Effects of Floor and Roof Truss Systems

The load testing for both the wooden floor and roof truss systems resulted in small strains in members with the max strain about 50 microstrain from the floor test and about 70 microstrain from the roof test at a loading of 550 lbs, because 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, for the floor system a modulus of elasticity of 1.85 msi would match the field test results well while for the roof truss a modulus of elasticity of 0.85 msi would match the roof load test results closely. 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 Tulous are able to maintain their structural strength over such a long period of years [15]. This assumption was confirmed by Wang [21] who states that China-Fir is used in the construction of the Hakka Tulous. If one is to model both the wooden floor system and roof truss using the conservative parameters found for the Chengqi roof wood in Table 4, the system is still found to be structurally sound. By using the modulus of elasticity of 175461 psi, we find that a max stress of 9 psi occurs in the floor system and a max stress of 13 psi occurs in the roof system. These values are far smaller than the ultimate strength 3990 psi of the material and so it can be said that even though material testing and load testing results did not concur with each other, both show that the system is structurally sound. For analysis purposes, the more accurate data likely come from load testing as the whole system is considered during testing, while the material testing is based on only small cut out samples of larger beams. Hence, a modulus of elasticity of 1.85 msi for the floor beam and 0.85 msi for the roof truss beam are used to address their load sharing effects at next paragraph. 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.

Table 7: Load Sharing Effects of Floor and Roof Truss Systems of Chengqi Tulou

	Floor System at 550 lbs		Roof Truss at 550 lbs	
	Structure Considered	Strain at Loading Beam (με)	Structure Considered	Strain at Loading Beam (με)
a) Field Load Test Data, Pinned Connection for All Members		32		70
b) RISA 2D Model Data, Pinned Connection for All Members		32 (E=1.85 msi)		70 (E=0.85 msi)
c) Simple Beam, Two Equal Concentrated Loads Symmetrically Placed		68 (E=1.85 msi)		311 (E=0.85 msi)
d) Beam Fixed at Both Ends, Two Equal Concentrated Loads Symmetrically Placed		17 (E=1.85 msi)		101 (E=0.85 msi)

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 as represented by Cases c) and d) in Table 7.

For a simply supported beam with two equal concentrated loads symmetrically placed, as shown in Case c) of Table 7, the maximal strain can be determined by the following equation:

$$\varepsilon = \frac{16Pa}{\pi D^3 E} \qquad (1)$$

Where ε is the strain, P is the total load, a is the distance of the loading point away from the support, D is the diameter and E is the modulus of elasticity. For a beam fixed at both ends, with two equal concentrated loads symmetrically placed, as shown in Case d) of Table 7, the maximal strain can be determined by the following equation:

$$\varepsilon = \left(\frac{a}{l}\right)\frac{16Pa}{\pi D^3 E} \qquad (2)$$

Where l is the length of the beam.

For the floor test, l= 80 inches, a= 20 inches, D= 7.63 inches, P= 550 lbs, E= 1.85 msi as per from Case b) of Table 7, Equations 1 and 2 give a maximal strain of 68 $\mu\varepsilon$ and 17 $\mu\varepsilon$, respectively; For the roof truss test, l= 114 inches, a= 37 inches, D= 7.32 inches, P= 550 lbs, E= 0.85 msi as per from Case b) of Table 7, Equations 1 and 2 give a maximal strain of 311 $\mu\varepsilon$ and 101 $\mu\varepsilon$, respectively. All these values are listed in Table 7 and compared with the strain data from field load tests.

As presented in Table 7, one can observe 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.

6. Self Healing Crack of Huanji Tulou?

Rammed earth structures have existed on this earth for thousands of years in regions that exhibit 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 these 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 Tulous 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. After the earthquake, it was reported that a crack had formed on the rammed earth wall measuring 20 cm in width and 3 meters in length. The locals claim that this crack has self healed since the earthquake [22, 23]. Figure 30 shows the crack that has formed in the walls of the Huanji Tulou, under the 1918 earthquake activity.

Huanjilou Tulou has an O/D 43.2m and 20m in height. The crack is about 10 meter above the ground. To access and examine the crack, a construction worker was hired to build an access platform using bamboo to that height during field study (Figure 31). After measuring the crack during the field study in the summer of 2009, including use of laser distance to measure its depth, it has been found that the crack is 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 is 178 cm in height, 5 to 10 cm in width, and 93 cm in depth. As shown in Figure 32, this crack is across the entire wall thickness and there are no wall ribs in the 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 can possibly be explained scientifically. In order to further analyze the structural behavior of the Hakka Tulou buildings, finite element modeling was used to duplicate the structural behavior experienced in real world conditions. Figure 33 shows the 3D model using the modulus of elasticity values reported in Table 4 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 30: Huanji Tulou Crack After Earthquake

Figure 31: The Location of Huanji Tulou Wall Crack and the Access Platform Used during Field Study

Figure 32: The Through-the-Wall Thickness Crack of Huanji Tulou

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 is not shown nor was 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 Tulous. 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 [24].

Figure 33 also shows the thermal expansion of the structure in response to 70 F thermal variation, while Figure 34 shows deformed shape of the crack after a -70° F temperature load was applied to the entire structure. With 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.

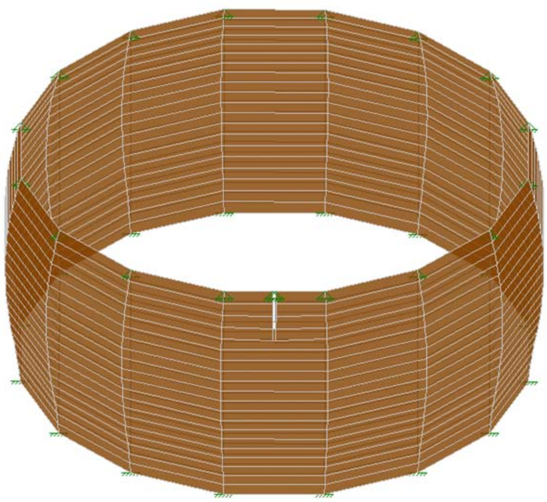


Figure 33: Huanji Tulou Crack Model and its Response to Thermal Load, 70°F

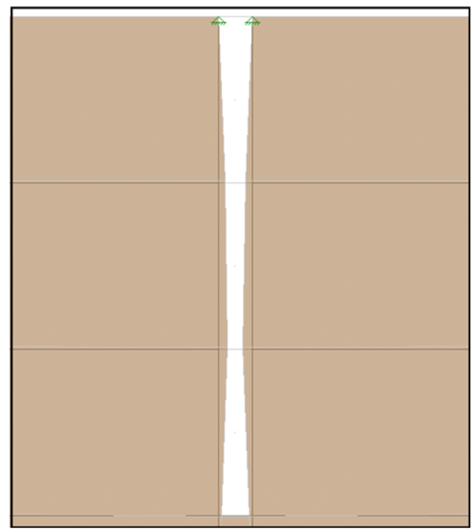


Figure 34: Crack Shrinkage due to -70°F

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 [25]. The key component to lime is calcium. However, Figure 8 EDS chart for Huanji Tulou indicates no calcium in its rammed earth.

We intended to use IRT to verify whether this crack has autogenously healed as reported by the locals. As discussed in Section 4.3, IRT is not able to detect the bonding mode between the earth and wall rib, and Huanji Tulou does not have wall ribs at all. 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 35. 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 35: The Cracking and Cavity at Lintel End

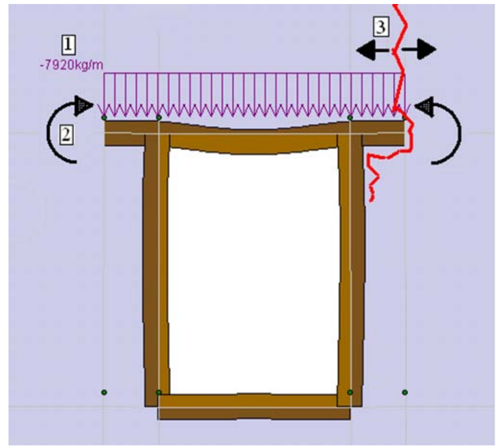


Figure 36: Lintel Behavior

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 35) has been accurately modeled using FE analysis, based on Lintel behavior as shown in Figure 36 along with an earthquake load, using the material property data generated from this study. Figure 37 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 [26]. 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 7.

7. Earthquake Resistance of Hakka Tulous

The Hakka Tulous have survived strong earthquakes for hundreds of years. 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. To further understand this behavior in Hakka Tulous, 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 [27]. 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 the modeled rammed earth is being taken as 1705.5 psi the study is being taken as conservative. 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 and this value is the most conservative found through material testing of other Tulous.

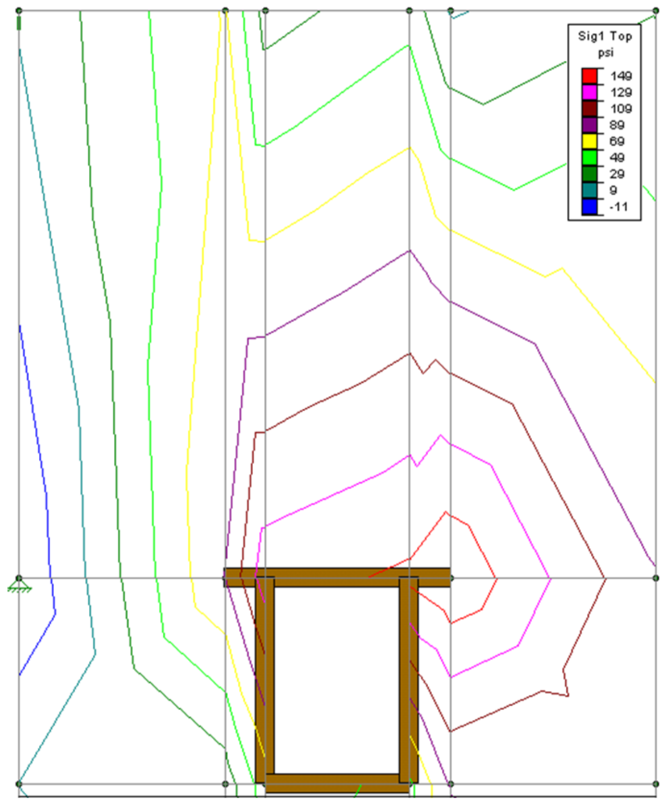


Figure 37: Stress in Vertical Direction due to Horizontal Load Induced by Earthquake

There are two important equations that are used in the simplified lateral force analysis and both can be seen Equations 3 and 4, respectively [27]:

$$V = \frac{F\,S_{DS}}{R}W \tag{3}$$

$$S_{DS} = \frac{2}{3}F_a S_s \tag{4}$$

Equation 3 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 4. '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 [27].

The Global Seismic Hazard Assessment Program (GSHAP) has compiled seismic maps from all around the world. The seismic map for China, which can be seen in Figure 38, 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 [28].

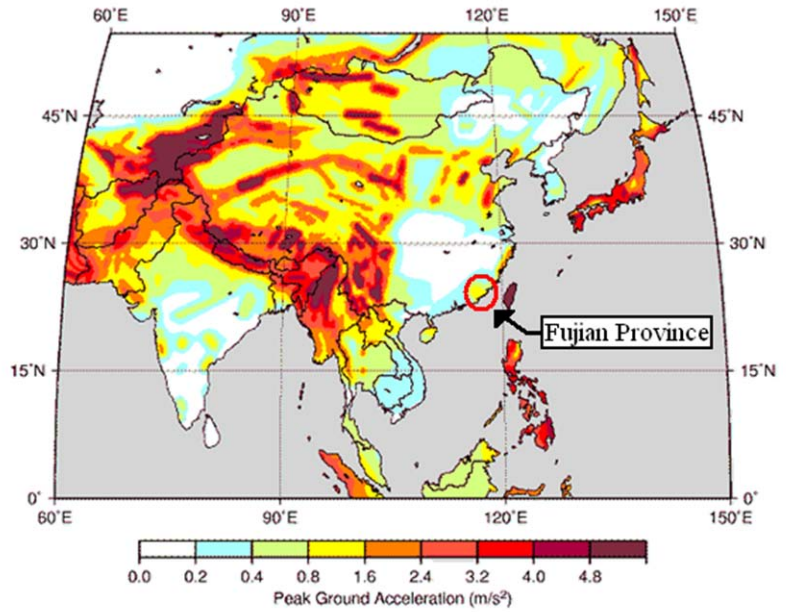


Figure 38: China Seismic Map [28]

From Figure 38 it can be seen that 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, 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 [29]. 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 4, one gets a 'S_{DS}' value of 1.0. One can then plug this 'S_{DS}' value back into Equation 3, which simplifies into what can be seen in Equation 5:

$$V = .8W \qquad (5)$$

Equation 5 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 6:

$$F_x = \frac{w_x}{W} V \qquad (6)$$

In Equation 6, '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 [31]. 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 [31]. As rammed earth is a brittle material, analysis of the material will be performed using this maximum stress theory. Figure 39 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 39 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.

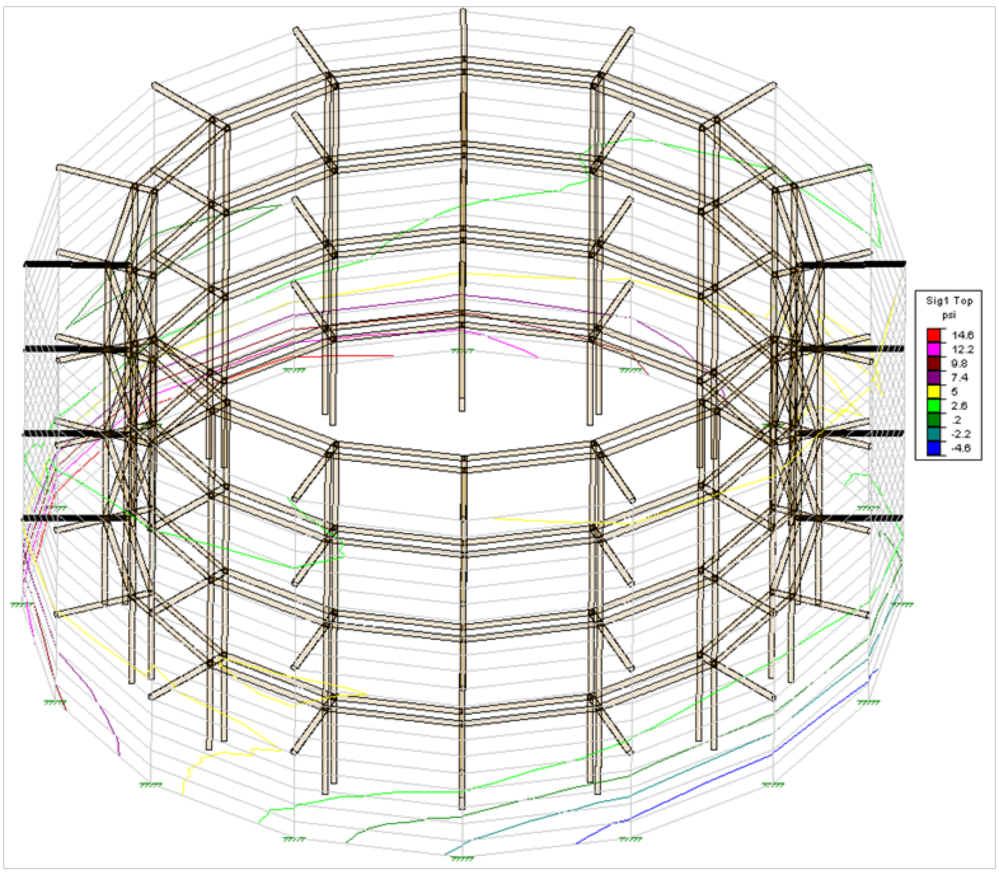


Figure 39: 3D Earthquake Stress Distribution of Huanji Tulou with Inner Wooden Systems

As can be seen in Figure 39, 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 3), 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 4.3, those wall ribs greatly enhance the earth walls.

Hence, 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.

8. Thermal Comfort Analysis of Living in Hakka Tulous

Within the walls of the Hakka Tulous, many families live in comfort during both the summer and winter temperatures that the climate within the Fujian Province of China produces. 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. Due to the close proximity of the Fujian Province to the equator the winters tend to be very mild and the summers are fairly hot.

Table 8: Temperature Data of Chengqi Tulou (Field Collected on 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		t_{Li}	t_1			t_2	t_{La}
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

Table 9: Relative Humidity Data of Chengqi Tulou (Field Collected on 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

In the case of this thermal analysis the heat transfer is from conduction, which means that heat energy is transferred from molecule to molecule until temperature equilibrium is reached [32]. 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. Both thermal resistivity and thermal mass play a key role in determining the thermal comfort of an area. 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 [33]. 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 [34]. 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 [34]. In order to display how effective the use of high thermal mass has been implemented in the Hakka Tulous, temperature and humidity data were recorded. During July 1, 2009, temperature readings were recorded at the Chengqi Tulou by West Virginia University and are shown in Table 8, while the collected relative humidity data are shown in Table 9.

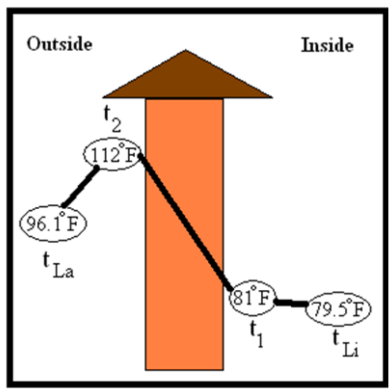


Figure 40: Schematic of the Chengqi Tulou Temperature Profile on a Summer Day

Table 8 shows temperatures recorded at four 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 8, the hottest that the outer surface of the rammed earth wall ever became was 112° F with a temperature profile in and outside Tulou shown in Figure 40. Since this is the most extreme temperature difference from our data, we can use this set of temperatures from 15:20 to calculate the thermal resistivity in situ using the equation below [35]:

$$r = - \frac{1}{a_{FAN}} + \frac{1}{\Lambda} + \frac{1}{a_i} \qquad (7)$$

where the equation's factors use all the four temperatures provided in Table 8 as well as the thermal conductivity of rammed earth, which is assumed to be similar to that of a clay brick, $0.91\frac{w}{m-k}$ [36]. The above equation gives us with a thermal resistivity of $1.0986 \frac{m-k}{w}$.

More commonly, materials are rated on their thermal resistance, which is denoted as the 'R' value. The 'R' value represents the ability of a thickness of a given material 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 divide it by the assumed value for thermal conductivity of $0.91\frac{m-k}{w}$. This method is the same as multiplying the thickness of the rammed earth wall to the "r" value of $1.0986 \frac{m-k}{w}$. Performing such operations results in a 'R' value of $11.24 \frac{ft^2-F^\circ-hr}{BTU}$. To get this 'R' value into the standard 'R-#' format that you see materials rated by 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 $\frac{ft^2-F^\circ-hr}{BTU}$ for every inch of rammed earth wall. With a thermal resistance rating of R-0.16 per inch of material, the rammed earth walls of the Tulou structure proves what was initially assumed, that a dense material is not a good thermal resistor. It is interesting to note that the rammed earth wall's thermal resistance is similar to that of concrete which is rated at R-0.10 per inch [37].

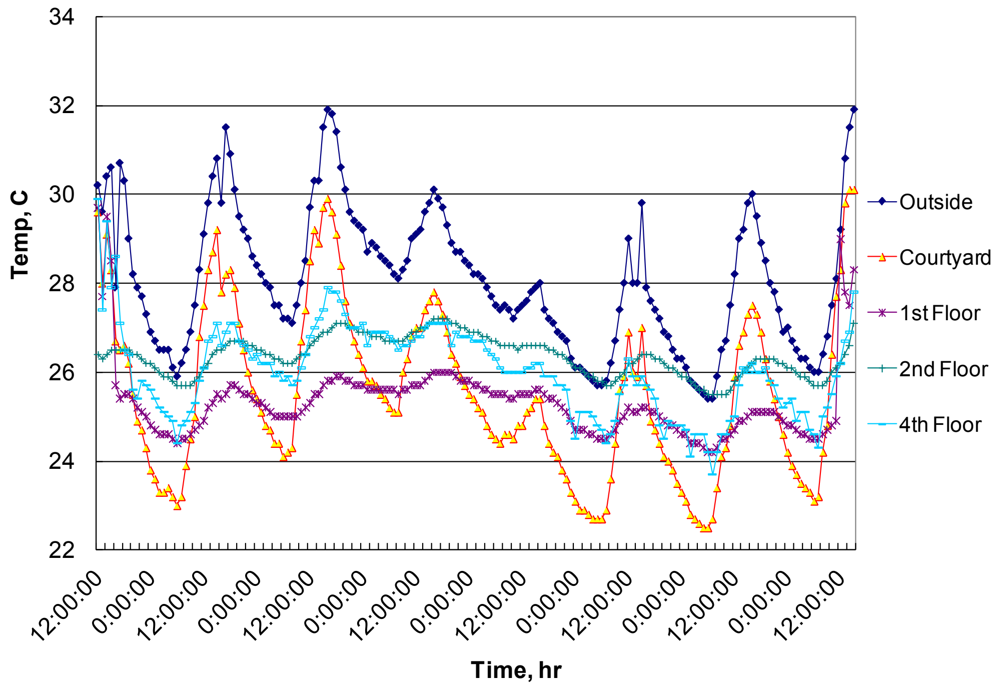


Figure 41: Chengqi Tulou 7-Day Temperature Data [39]

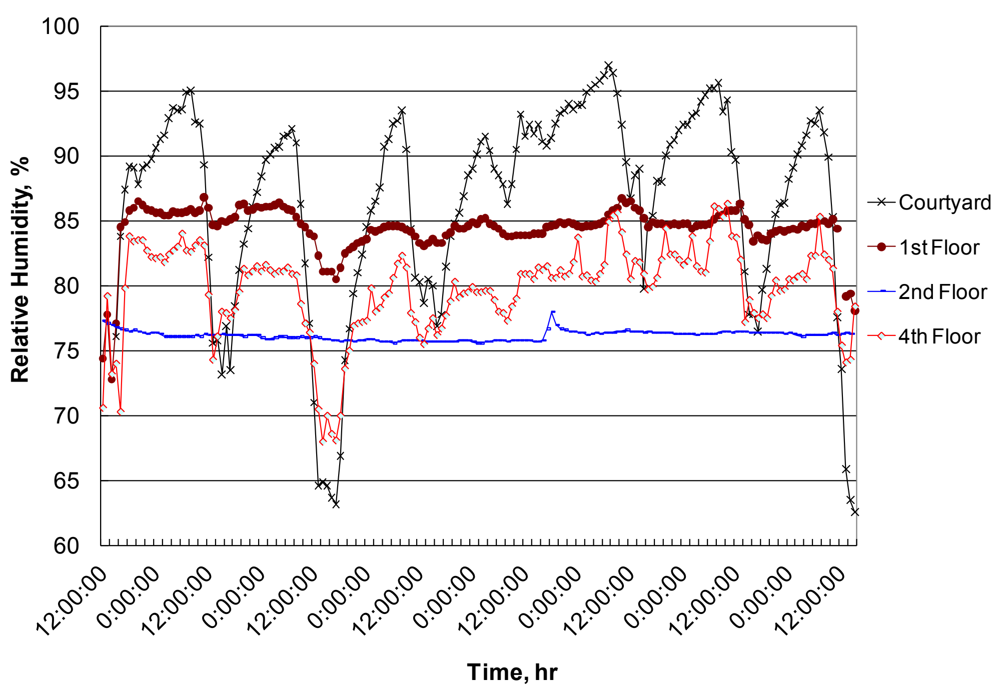


Figure 42: Chengqi Tulou 7-Day Humidity Data [39]

The Hakka Tulous have little to 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 where as 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 [34]. These thermal comfort benefits have also been observed in cave dwelling [38].

Figures 41 and 42 show 7 day temperature and humidity data, respectively, from the Chengqi Tulou that were collected from June 29 to July 6, 2009 using 5 Data Loggers [39]. These data were recorded at 5 different locations, i.e. outside, inside the courtyard, and inside on the 1st, 2nd, and 4th floors. As can be seen in Figure 41, the outside temperatures in both the courtyard and outside the Tulou are diurnal and range more than 7° Celsius, which already tells us that the application of thermal mass is efficient for the climate as thermal mass is most effectively used in climates with a diurnal temperature range of 6° Celsius or more [34]. Figure 41 also shows the success of the application of the rammed earth walls as the 1st, 2nd, and 4th floor interior temperatures are very stable, staying within a comfort zone and showing temperature fluctuations, in most cases, of no more than 1° C. In Figure 42, the humidity data show us that while humidity fluctuates outside in the courtyard to values as high as 97%, the interior humidity percentage remains constant with the most efficient floor remaining at 76% humidity throughout the entire week. Along with the humidity data in Table 9 that included the humidity values measured inside the wall, one can conclude that the rammed earth wall also regulate the room humidity. As displayed from these data, the thermal comfort zone is achieved due to the effective use of thermal mass from the rammed earth walls.

The Hakka people found ways to live in thermal comfort without the need of mechanical heating or cooling in both the summer and winter seasons due to their effective use of rammed earth construction. This was also done without the use of insulation, which would help better maintain heat within the structure during the winter seasons. Modern construction can take what the Hakka people created and make it even more efficient. As stated by Sustainable Energy Authority, Victoria, mud bricks, similar to rammed earth, are very efficient during the summer however during the winter tend to be less efficient due to their small 'R' value, or thermal resistance, allowing the cool air to take heat away from the structure. Modern construction can take advantage of using both insulation and natural earth construction in a way that allows for rammed earth construction to become a highly efficient natural construction material in all seasons.

9. Potential Extension of Hakka Rammed Earth Technology to Modern Sustainable Construction

The sustainability of Hakka village dwellings built hundreds of years ago and still in-use today might provide us with new approaches with reference to green building movement including Leadership in Energy and Environmental Design (LEED) program [40]. As per NSF Emerging Frontiers in Research and Innovation - Science in Energy and Environmental Design: Engineering Sustainable Buildings program announcement, "In the US, buildings are responsible for 38% of carbon dioxide emissions, 71% of electricity consumption, 39% of energy use, 12% of water consumption, and 40% of non-industrial waste. We spend 90% of our time indoors and the indoor environment affects our physical and mental health and our productivity." This statement has been well represented through ecological footprint data. The 2006 ecological footprint is 9.6 global hectares (gha) per person for US with reference to only 0.63 gha per person for Hakka community and 2.7 gha per person on average in the world [41]. Hence sustainability concepts have to be integrated into design and construction of next generation buildings in industrial nations.

More specifically, we wish to emulate the Hakka Tulou rammed earth construction technology with appropriate modifications, for implementation in modern construction leading to: 1) energy-efficient and green buildings with thermal comfort; 2) disaster resistant structural configurations; 3) innovations of affordable housing and multi-story buildings; and 4) development of durable rammed earth material systems and construction techniques.

The key materials used in Hakka Tulous are rammed earth and wood that are sustainable construction materials. Through this study, one can see that there are numerous benefits that rammed earth construction offers the Hakka people. The rammed earth walls, even consisting voids and cracks, are structurally sound as proven by the hundreds of years of service even through numerous natural disasters. Rammed earth also provides the Hakka people with thermal living comfort during summer and winter periods due to the material's high thermal mass, showing temperature differences of around 5-15 F between indoor and outdoor temperatures. Seeing the modern lifestyle that rammed earth structures can offer their tenants, people may question what is the difference between rammed earth construction and modern construction?

Modern construction focuses much more on the use of concrete in structures as it too has a high thermal mass and even higher material strength than that of rammed earth. The benefit to using rammed earth lies in its numerous environmental benefits including zero CO_2 emissions when compared to concrete and steel. Rammed earth is a completely natural material that involves a timely production process involving compressing a natural mixture of earth, rock, and other materials. This process releases zero CO_2 during and after the fabrication process of rammed earth, while wood comes from trees that absorb CO_2 through photosynthesis process that converts carbon dioxide into organic compounds, using the energy from sunlight. Cement production on the other hand, a common ingredient in concrete, releases anywhere from 5-10% of the world's total CO_2 emissions into the earth's atmosphere [42]. As already known, CO_2 emissions have been an important topic of debate as CO_2 is listed as one of the more common greenhouse gases in existence. Other benefits from rammed earth construction include its recycleability, low operation cost, and cost savings in material, transportation, and energy. With the Hakka Tulous serving as a prime example of what rammed earth construction can offer, rammed earth could prove as a viable building material option over that of concrete. Modern rammed earth construction can take what the Hakka people created and make it even more energy-efficient. Examples of modern rammed earth constructions are shown in Figure 43.

Figure 43: Modern Rammed Earth Construction [5]

When one is to consider the LEED green building certification program developed by the U.S. Green Building Council, USGBC, one could expect only the highest certification for the Hakka Tulou rammed earth buildings. The LEED certification is based on, "energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts [40]".

The Hakka Tulous deserve the highest level of LEED certification as the structures show the greatest energy savings with no additional heating and cooling required and there are zero CO_2 emissions thanks to the main building material of rammed earth. Rammed earth also provides the interior space with humidity control and the walls blend in well with the natural surroundings of the Fujian province. Rammed earth has stood the test of time in historic constructions and due to its numerous advantages can surely be seen as a viable building material option of the future.

Figure 44: Round Houses Built by Deltec Homes [44]

Figure 45: Modern "Tulou" under Construction in Guangzhou, China (Designed by Urbanus) [45]

Other than the materials, Hakka Tulous offer outstanding architectural designs that have existed for over one thousand years and survived from several major earthquakes and numerous hurricanes. Our FE modeling of this study has demonstrated those Hakka Tulou structures' superior earthquake resistance, while a Japanese research team has simulated Hakka Tulou's response under strong wind [43]. These observations and continuing effort may lead to potentially transformative research ideas for modern construction of more disaster resistant structures. For example, school building design and construction, in the paths of potential hurricanes, floods and tornadoes or in earthquake-prone regions, might adopt the style of Hakka Tulou structures. It was reported that the round single family houses built by Deltec Homes Inc as shown in Figure 44, were much more hurricane resistant and energy efficient than conventional houses [44]. When Hurricane Katrina struck the Gulf Coast in 2005, none of the Deltec homes in her path suffered any structural damage from Katrina's category 5 hurricane force winds, because there is not enough surface area on any part of the round house for pressure to build up. In addition, their less exposed surface area than square house offer superior energy efficiency and improved durability [44]. The style and design of Hakka Tulous might be also emulated for construction of multi-story, multi- family dwellings in city. A design group named Urbanus in Shenzhen, China is currently experimenting Hakka Tulou concept in Guangzhou, China as a solution to provided affordable housing for people and the experimental project, a round apartment as shown in Figure 45, incorporates 278 apartment units, a dormitory, a small hotel, shops, a gymnasium, a library, and various public spaces [45].

To disseminate our research findings and facilitate the potential extension of Hakka technology to modern construction, the PIs in cooperation with XMU and ASH organized and presented at the Forum on Hakka Tulous: Lessons to Be Learned, Past, Present and Future that took place on June 24, 2009, at Xiamen University, China (Figure 46) [46, 47]. The objectives of the Forum were 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. The Forum, open to general public at no cost, consisted of two sessions and eight presentations [12]. There were over 130 people in the audience. The PIs are currently organizing the Hakka Tulou Forum 2011 that will take place as a special session of the International Symposium on Innovation & Sustainability of Structures in Civil Engineering 2011 on Oct 28-30, 2011, Xiamen University, China. Our presentation at the 85th Annual Meeting of the West Virginia Academy of Science, Morgantown, WV has also created some interests and good discussions among audience [48]. The PI is going to attend the upcoming 2011 NSF Engineering Research and Innovation Conference: Engineering for Sustainability and Prosperity, Jan 4-7, 2011, Atlanta, GA. The team will exhibit a poster during the conference and has contributed a research highlight and a technical paper [49]. In addition, Hakka Tulou was recognized with the first "History Made for Tomorrow" award by US History Channel on October 21, 2010 [50]. The PI cooperated with the US History Channel crew to make the History Made for Tomorrow piece on Hakka Tulous during field study in the summer of 2009. The "History, Made for Tomorrow" is a new community outreach program to show case historic places where lessons can be learned to build a sustainable 21st century.

Figure 46: Hakka Tulou Forum 2009 in Session, June 24, 2009, Xiamen University, China

10. Conclusions

Through this study we have investigated the in-service World Heritage Hakka rammed earth structures, i.e. Fujian Tulou of China, in terms of their material and structural responses under thermal and mechanical including earthquake loads. The investigation included field evaluations of several Hakka Tulous using nondestructive testing techniques such as infrared thermography, rebound hammer, ultrasonic testing, in-situ full scale load testing on roof truss and floor systems, and thermocouples for thermal data. The field data were processed at WVU and integrated with new data generated from material characterization of field collected samples at both WVU and XMU laboratories. Finite element modeling was conducted to simulate those material and structural responses to arrive at better understanding.

Radiocarbon dating test of a wooden sample from Chengqi Tulou has verified the building's completion date of around 1709. Scanning electron microscopy and chemical characterization through elemental analysis revealed the difference in constituent materials among the rammed earth samples of Tulou buildings studied. Rich amount of calcium was found only in the Fuxing Tulou's earth sample. Fuxing Tulou was built in 769 and is the oldest square Tulou in the area. Its rammed earth wall was made of red soil, lime and pebbles. The extensive use of lime in its rammed earth wall formulation explained why Fuxing Tulou has been extremely durable. Strength and stiffness property data were generated for the constituent materials used in rammed earth wall construction including rammed earth, wood and bamboo. The results show that Fuxing Tulou earth sample is stronger and harder than younger Tulous. This study found that 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. NDT 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 structural integrity of floor and roof truss members in the Chengqi Tulou building was evaluated by collecting strain data in response to an external load. The field strain measurements and structural analyses including computer modeling conclude that both the wooden roof truss and floor systems are structurally sound and efficient even with the high age of the structure. Their load versus strain scenarios can be idealized through simple beam with fixed end model as opposed to a simple beam bending model. The result demonstrates that the jointed neighboring members have a high load-sharing effect in a manner similar to a fixed beam. On the roof truss, 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 even surpass those of a fixed beam.

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 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 field collected thermal data and analysis conclude that the Hakka people found ways to live in thermal comfort without the need of mechanical heating or cooling in both the summer and winter seasons due to their effective use of rammed earth construction. Because of the rammed earth wall's high thermal mass, during the warm summer season the material absorbs the heat from the outside while keeping the interior cool during the day. At night the material releases the heat to keep the interior temperature stable when compared to the colder night temperatures outside. During the winter the material is heated by direct sunlight in order to release heat and keep the interior temperatures at a comfortable level.

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 and have advanced the understanding of the thermo-mechanical and aging responses of those structures. This work hopefully 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. This work will also broaden our cultural understanding of the Hakka people. It is wise to look at our past history and learn from it, just as the Hakka people learned how to advance and improve their structures from knowledge and experience that has been acquired from several centuries. Although we may be looking at a building material that was prevalently used in the past, rammed earth could very well be tailored to our future use. By using science and combining what we know of rammed earth from the Hakka people, the efficiencies of rammed earth can be expanded and used in more widespread modern construction. Such construction methods would reduce our need for using concrete and thus reduce our greenhouse gas emissions for a more sustainable future of our planet earth.

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