Annual Report for Period: 01/2009 - 12/2009
Submitted on: 12/31/2009
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: Yes
Contribution to Project:

Post-doc

Graduate Student

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

Teamed with:
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Consulted with:
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Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

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

Training and Development:

The graduate student and technician at Xiamen University who participated in the work got to learn the most advanced portable infrared thermography scanning camera and infrared temperature gun.

The project also provided them two week long opportunity to work with an international team and communicate in English.

Outreach Activities:

While visiting Xiamen University, Drs Hota and Liang have interacted with over 80 graduates and undergraduates who are new to Polymer Composites and their applications. One of them has submitted application materials for consideration of admission into Fall 2010 MSCE program at WVU working in area of rehabilitation using FRP composites.

Journal Publications

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

The PIs have introduced Green Building Movement in USA including Leadership in Energy and Environmental Design (LEED) program to over 130 people who attended the Hakka Tulou Forum thru our three 20 minute long presentations.

Contributions to Other Disciplines:

This project has enabled us to extend our arm in area of materials and sustainable structures to team with other 8 faculty from three colleges to submit a NSF EFRI- SEED pre -proposal, entitled 'Planning, Design and Construction of Sustainable Buildings: A Systems Approach'.

Contributions to Human Resource Development:

Our work has stimulated one graduate student at Xiamen University to work with us to pursuit his PhD on the subject, that is, to use both creativity and vision to adapt and transform historic Hakka architecture and life style to meet the needs of sustainable future.

One (American) graduate student will be working on the project in Spring 2010. This will greatly promote cross-culture exchange.

Contributions to Resources for Research and Education:

Thru this project, we started a Forum series. The Forum on Hakka Tulous: 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 are just beginning to plan the Forum in 2011.

Contributions Beyond Science and Engineering:

We worked with HISTORY Made for Tomorrow program on Hakka Tulou. They are producing two pieces: one is running 12 minutes while another will be a 23 minute (TV half hour) program. These two pieces will reach millions.

We founded an International Hakka Tulou Alliance (IHTA) last summer. IHTA will aim to help save, preserve and revitalize Hakka Villages for our common world heritage and a more sustainable future of planet earth; and to emulate Hakka Tulou technologies for design, construction, operation, and maintenance of future green structures.

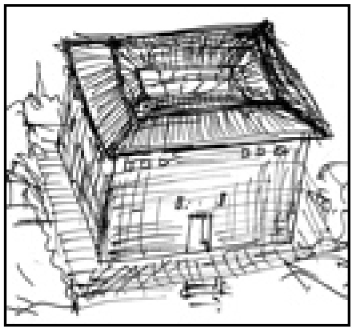
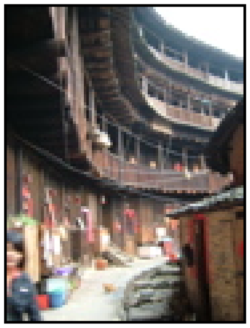
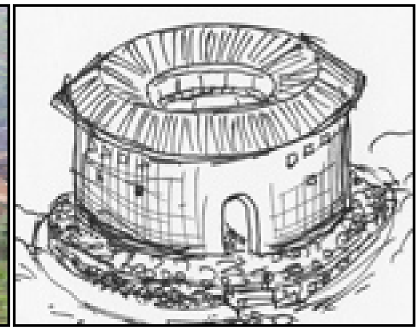
Conference Proceedings

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
Any Book
Any Web/Internet Site
Any Product
Any Conference

Forum on Hakka Tulous: Lessons to Be Learned, Past, Present and Future
+Launch of the International Hakka Tulou Alliance (IHTA) (in Mandarin & English)

Time: June 24, 2009, 2:30 -6:30 PM **Place:** Xiamen University, Xiamen, China

Organized by

Constructed Facilities Center, West Virginia University, Morgantown, West Virginia, USA
ASH-Autonomous & Sustainable Housing Inc, Calgary, Alberta, Canada
School of Architecture and Civil Engineering, Xiamen University, Xiamen, Fujian, China

Special thanks to History Channel History, Made for Tomorrow for honorary support

Introduction: Rammed earth is a sustainable construction material due to many benefits for the environment including: 1) natural (non processed) material, 2) universal availability, 3) durability, 4) recyclability, 5) low embodied energy, 6) low CO2 emissions, 7) high thermal mass, 8) traditional construction method, and 9) low cost for material, construction, transportation. **Hakka Tulous** in Fujian Province of China, reflect the importance of historical precedents, universal evolution, emerging innovation and advancement in the science and engineering of rammed earth construction, from 8th century to 20th century. Tulous can be considered as "EcoVillages" of best practices for planet earth's sustainability in their planning, design, construction, lifestyle, resource management, micro industries, renewable energy, recycling of human and animal waste, and a low ecological footprint. This forum will interest leading academics, architects, builders, developers and suppliers.

Objectives: This forum will serve to demonstrate how the sustainability of Hakka village architecture built hundreds of years ago and still in partial use today, bridge the past, present and future, with exemplary lessons for our modern world. This forum will also serve as the official launch of the International Hakka Tulou Alliance to help save, preserve and revitalize Hakka Villages for our common world heritage and a more sustainable future of planet earth.

Co-Chairs: Hota Gangarao, Professor and Director, CFC-WVU
Ying Lei, Professor and Associate Dean, ACE-XMU

Agenda: (Each presentation will allow 3 minutes for questions and discussions.)

2:30 - 2:40	Opening Remarks and Introduction – Ying Lei
2:40 - 2:50	Speech by Ms Zhang, Deputy Mayor of Longyan City, Fujian Province, China
2:50 - 3:10	Overview of Hakka Tulou Architecture – Minoru Ueda, Japan
3:10 - 3:30	Fujian Tulou and Science: A NSF Project Prospectus – Liang and Hota, U.S.A.
3:30 - 3:50	UN Hakka Biosphere and Tulou Retrofit – Jorg and Helen Ostrowski, Canada
3:50 - 4:10	Learn from Tulou – Shaosen Wang, China
4:10 - 4:20	Break (Refreshments served)
4:20 - 4:40	Traditional Environmental Knowledge in Hakka Vernacular Architecture - Kawai/Kobayashi, Japan
4:40 - 5:00	Fujian Tulou: Past, Present and Future – Xiaodong Lai, World Heritage Fujian Tulou Yongding Site
5:00 - 5:20	My Field Experience: Hakka and Weilongwu Culture – Fang Xuejia, China
5:20 - 5:40	Applying Hakka Wisdom to Future Sustainable Structures: Proposal - Liang/ Ostrowski/Lei/Hota
5:40 - 5:50	International Hakka Tulou Alliance (IHTA): Proposal – Ostrowski/Liang
5:50 - 6:00	Speech by Shuzhi Lin, Chief Engineer, Xiamen Construction and Administration
6:00 - 6:10	Concluding Remarks – Hota Gangarao
6:30	Banquet for invited guests only

For more information, please contact with **:** Ruifeng Liang, rliang@mail.wvu.edu, (304) 293 9348,
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Activities

Summary

Rammed earth is a sustainable construction material with many positive attributes to the environment compared to concrete and steel. The in-service World Heritage Hakka rammed earth structures, i.e. Fujian Tulou of China, are historic and unique in design and performance. These buildings reflect the emergence of innovation, evolution, and advancement of the science and engineering of rammed earth structural construction from 8th century to 20th century.

In collaboration with the School of Architecture and Civil Engineering, Xiamen University, China and ASH-Autonomous & Sustainable Housing Inc, Canada, the PIs of West Virginia University Constructed Facilities Center traveled to China during June 15 - July 15, 2009 and field-investigated the material and structural responses of historic Hakka rammed earth buildings. A Forum of over 130 people on Hakka Tulou was conducted on June 24, 2009 at Xiamen University, China. The forum was to demonstrate the sustainability of Hakka village dwellings built hundreds of years ago and still in-use today and to bridge the past, present and future, with exemplary lessons for our modern world. In addition, the team also assisted the US History Channel crew to film the episode “Hakka Tulou Village” as part of the new series "History, Made for Tomorrow".

All field studies were conducted in a nondestructive manner using techniques such as InfraRed Thermography (IRT) Scanning Camera, Rebound Hammer, Ultra-Sonic Testing Device, strain data acquisition from load tests on roof truss and floor components through strain sensors, and thermal data acquisition from thermocouples, in addition to collecting humidity data. The data collected from the field trip were further processed on-campus for their implications and the samples collected were further tested at laboratories for their mechanical properties. More morphological, thermal and mechanical tests of the samples collected from the field are being continued at CFC-WVU laboratories, in addition to carbon dating for the age of buildings. Then the research is to be followed by finite element modeling of the material and structural responses of Tulou buildings, that will be conducted in Spring 2010. Upon completion of the research we wish to emulate the Hakka Tulou Technologies for implementation in modern constructions, leading to: 1) durable rammed earth material systems; 2) advanced rammed earth construction technique using reinforcing wall ribs; 3) affordable housing and space-efficient office towers in urban areas; 4) disaster-resistant structural configurations; and 5) energy-efficient and green buildings.

The activities conducted during year 2009 included field study plan development prior to travel, field study in China, post trip data processing and laboratory testing, and other related efforts elaborated as follows.

1. Field Study Plan Development and Trip Preparation

Field study will succeed only when ones get fully prepared. For example, due to limitation in hand-carried equipment, the PIs can only carry small size research tools. Load testing equipment including data acquisition system, and core extraction machine have to be arranged well ahead for field use, in cooperation with Xiamen University. Preparation work prior to travel to China included: 1) reviewing of reports and articles on Hakka earth structures with historic perspective of material selection and structural design; 2) communicating with Jorg Ostrowski regarding his perspective and understanding of Hakka buildings; 3) pre-visit selecting of Tulou structures for field data collection; 4) development of a plan of field study; 5) seeking inputs and comments on the plan and revising; 6) preparing research equipment and tools; 7) coordinating among team members in terms of scheduling and responsibility; 8) coordination with local Government officials; and 9) travel document.

The PIs prepared a draft Plan of Field Study and sent out to team members for review on April 22, 2009. Jorg Ostrowski returned his comments on May 10, 2009. A refined version of plan of field study was completed on May 30, 2009. The plan had specific details regarding research topics, objectives and action items, tentative schedule, work site and subject Tulou buildings, possible options, participants (manpower), research equipment & tools and other resources needed, challenges/difficulties, notes. The team was named as "Fujian Tulou & Science" International Exploratory Research Team. There were extensive info exchange and discussions on the details of the field study plan and research tools between team members prior to travel.

The PIs worked with Dr John Kuhlman and FLIR Systems, Inc. for a month (May 8 to June 9, 2009) to complete an AES (Automated Export System) transaction and obtain an ITN (Internal Transaction Number), in order to hand-carry a portable FLIR BCAM SD Infra Red Thermography Scan Camera into China for the proposed study. The preparation also included communication with NSF Beijing Office prior to travel and travel to DC China embassy to apply for entry visa.

2. General Tour and Selection of Tulou Buildings for Data Collection (June 20-23, 2009)

The team including Hota, Liang, Lei, Jorg, Helen, and Lee arrived in Yongding from Xiamen at about 1:30pm, June 20, 2009 and were welcomed by Yongding Government officials. A bilateral meeting with local officials was held in the late afternoon. The objectives of the NSF research project were presented and based on those, an effective and practical schedule was decided.

The team visited Chuxi Village (June 21 AM, Figure 1), Hongkeng Village (June 21 PM, Figure2), Gaobei Village (June 22 AM), Nanxi Village (June 22 PM), all four located in Yongding County, Fujian Province; Hekeng Village (June 23 AM), Zigzag Building and Tianluokeng Village (June 23 PM), all three located in Nanjing County, Fujian Province. A discussion meeting was held in the late afternoon of June 22 to discuss and validate the field study plan that was proposed prior to China trip. The local Government officials and a Tour Guide accompanied the team during the tours. The team returned to Xiamen University in the evening of June 23, 2009 to prepare the Hakka Tulou Forum which took place on June 24, 2009.

The selected Tulou buildings for research were primarily located in Yongding County. Hongkeng Village was selected as our headquarter location while both Gaobei Village and Nanxi Village are about 3 miles away in opposite directions. During our entire field study, we were accommodated in a local hotel in Hukeng Town, which governs both Hongkeng and Nanxi Villages while Gaobei belongs to Gaotou Town.

Figure 1, Chuxi Tulou Group, Yongding, Fujian

Figure 2, A Team Photo, Zhencheng Lou, Hongkeng Village, Yongding, Fujian. L to R: Zhaoting Zhang, Jorg Ostrowski, Ruifeng Liang, Gangarao Hota, Ying Lei, Yuan Lee, Helen Ostrowski, Meiqun Lu

We have documented representative Tulou buildings from material and structural design perspective including variation in shape (square, round, others), status, age, stories, and number of stairways. These Tulou buildings were screened for direct field data collection from in-situ measurements including: 1) temperature and humidity (inside and outside, at different times of the day and at different season thru year-long monitoring) for thermal comfort analysis; 2) strain responses thru load tests (roof truss and floor beam); 3) structural dimensions using Laser distance measurer for FE structural modeling; 4) sizes and description of cracks that were reportedly caused by R.7 Earthquake to verify self-healing process; 5) Ultrasonic wave for estimating strength; 6) Rebound hammer; 7) Infrared thermography. Wall samples were also to be collected from the buildings selected with variation in ages for further laboratory evaluation.

3. Forum on Hakka Tulous: Lessons to Be Learned, Past, Present and Future (June 24, 2009)

West Virginia University Constructed Facilities Center (CFC-WVU, Morgantown, West Virginia, USA) in cooperation with ASH-Autonomous & Sustainable Housing Inc (Calgary, Alberta, Canada) and School of Architecture and Civil Engineering, Xiamen University (ACE-XMU, Xiamen, Fujian, China) organized the Forum on Hakka Tulous: Lessons to Be Learned, Past, Present and Future that took place on June 24, 2009, 2:30 -6:30 PM at Xiamen University. The Forum was open to general public at no cost. There were over 130 people in the audience, including Government Officials from Longyan City of Fujian Province, leading academics, architects, builders, developers and suppliers (Figures 3 and 4).

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 exemplary lessons for our modern world. The forum also served as the official launch of the International Hakka Tulou Alliance (IHTA) to help save, preserve and revitalize Hakka Villages for our common world heritage and a more sustainable future of planet earth.

The Forum was co-chaired by Hota Gangarao, Professor and Director of CFC-WVU and Ying Lei, Professor and Associate Dean of ACE-XMU. It consisted of two sessions separated by refreshments-served break. The forum began with introduction of guests and opening remarks by Dr Lei, followed with a welcome speech by Ms Xiujuan Zhang, Deputy Mayor of Longyan City of Fujian Province.

There were eight (8) presentations: 1) Overview of Hakka Tulou Architecture by Minoru Ueda of Japan, 2) Fujian Tulou and Science: A NSF Project Prospectus by Ray Liang and Gangarao Hota of United States, 3) UN Hakka Biosphere and Tulou Retrofit by Jorg and Helen Ostrowski of Canada, 4) Learn from Tulou by Shaosen Wang of China, 5) Traditional Environmental Knowledge in Hakka Vernacular Architecture by Kawai Hironao and Kobayashi Hiroshi of Japan, 6) Fujian Tulou: Past, Present and Future by Xiaodong Lai of China, 7) My Field Experience: Hakka and Weilongwu Culture by Fang Xuejia of China, 8) Applying Hakka Wisdom to Future Sustainable Structures: Proposal by Ray Liang/Jorg Ostrowski/Ying Lei/Gangarao Hota. Each presentation was 20 minutes in length including last few minutes for questions and discussions.

At the Forum, Ray Liang and Jorg Ostrowski introduced International Hakka Tulou Alliance (IHTA) to the audience, in terms of its objectives, organizational structure, operation, memberships and revenues for funds. IHTA will aim to help save, preserve and revitalize Hakka Villages for our common world heritage and a more sustainable future of planet earth; and to emulate Hakka Tulou technologies for design, construction, operation, and maintenance of future green structures. There will be no membership fee for individuals and a nominal fee for group/ organizations/ government agencies. IHTA is currently affiliated to CFC-WVU.

The forum was concluded with an enthusiastic support speech by Shuzhi Lin, Chief Engineer of Xiamen Construction and Administration and further with closing remarks by co-Chair Dr Hota. Finally, Dr Lei hosted a banquet for all invited guests. The Forum was a great success and many people in the audience provided feedbacks and their comments.

Figure 3, Full Room of Audience at the Forum

Figure 4, Extraordinary Poster of the Forum Produced by Dr Lei

4. Field Studies of Historic Hakka Tulou Buildings (June 26 –July 3, 2009)

The PI (Liang) headed a new team consisting of Mr Yanhao Li, Technician of Civil Engineering Department of XMU and Mr Yongqiang Jiang, graduate student assistant working with Dr Lei, hauled all the research equipment and tools, and returned to Hukeng Town, Yongding from Xiamen at 1:00pm, June 26, 2009. Again the team was welcomed by local Government officials including County and several Towns. The field study would involve Tulou buildings located in Hukeng Town, Gaotou Town and Hulei Town. The County Officials requested the Town officials to support our field study effort. Note that ASH team (Jorg/Helen Ostrowski, Minoru Ueda, and Yuan Lee) also returned to Yongding on June 26 but they had their own schedules and activities.

Specifically, the following Tulou buildings were studied in a nondestructive manner and some small size wall samples were collected for further laboratory evaluations:

Wuyun Tulou, located in Gaotou Village, Gaobei Town, June 26, 2009

Wuyunlou is a square Tulou with four-storey, front wall cracked and buckling (Figure 5). Inside, wooden poles provide support to protect the structure from collapse. A notice at the door forbids visitors from entering or climbing the stairs in case the structure crumbles, but three old people still live inside. Built around 1500 (Ming Dynasty), this is one of the oldest known rammed earth buildings in the village. It appears to be the first to benefit from restoration after the world heritage listing. The metal clamps on-site were utilized as weights in load tests conducted on Chengqi Lou.

We conducted ultrasonic scan (Figure 6), rebound hammer test (Figure 7), Infra Red Thermography (IRT) scan, and dimension measurements. We also tried to core-extract wall samples (2 inch diameter) but failed due to shattering (brittleness) of the rammed earth under vibration (Figures 8 and 9). Instead, some wall samples and wall ribs were collected from the building using a chisel.

Figure 5, Wuyun Square Tulou

Figure 6, Ultrasonic Testing Heads

Figure 7, Rebound Hammer

Figure 8, Core Extract Machine

Figure 9, Failure of Core Extraction

Figure 10, Fuxing Tulou

Fuxing Tulou, located in Hulei Town, June 27, 2009

Fuxinglou is the oldest square Tulou, built in 769 (Tang dynasty), 2 storey. Note that Hulei Town is one and half hour far away from Hukeng Town by car. Half burned in a war in 1852, the other half still in use by 8 families (Figure 10). The owner told us that in 1986, he intended to create a new side window for convenience. It was found that punching a hole on the wall was so difficult that it took 16 days to create the side window. The story illustrated how strong the wall has become as it ages for the past 1200 years.

We conducted IRT scan, ultrasonic scan, rebound hammer test, and dimension measurements. We tried again to core-extract wall samples (2 inch diameter) and failed due to shattering under vibration. Instead, some wall samples and wall ribs were collected from the building using a chisel.

Chengqi Tulou, located in Gaobei village, Gaotou Town, June 28-29, July 1-2, 2009

Chengqilou is well known as the King of Tulou (Figures 11 and 12). O/D 73m, 5376m2, 3 rings 1 center (ancestral shrine), 4 floors, 400 rooms, 2 wells, 3 gates. It took about 50 years (from 1662 to 1709) to complete the construction of this Tulou. It has 400 rooms. At its maximum, it accommodated 80 families for 800 people, currently housing 60 families about 400 people. Because of its remarkable scale and multi-ring structure, this building was adopted as Chinese stamp pattern since 1986.

We conducted temperature and humidity readings using thermocouples at different times of a day, and dimension measurements. In order to measure the wall temperature gradient across the wall, one thermocouple was placed one ft deep from outside surface while another thermocouple was at one ft deep from inside surface (the depth was limited by 3/8 inch center diamond carbide tip drill bit; note that we were not able to get to the center point of the wall considering it is 1.5m thick.). However, the rammed earth wall was so hard that the lock ring on hammer drill was broken while drilling. We had to purchase a replacement but the replace lock ring was broken while drilling the second hole.

All thermocouples were placed on the ground floor only, at about the same height as an adult. The locations were arrayed as follows (T-temp, H-humidity): inner center courtyard (T, H)/inner corridor (T, H)/inside room(T, H)/inner wall surface(T, H)/12" depth inside the wall from inner wall surface (T)/12" depth in wall from outside surface (T)/outer wall surface (T, H)/outside field (T, H), total 8 points. The data were recorded versus time of the day.

Figure 11, Chengqi Tulou

Figure 12, Inside Chengqi Tulou

Load tests on roof truss and floor beam were also conducted on this structure. About 15 strain gages were mounted in each type of test. Data acquisition system was provided by Dr Lei's group. We experienced some difficulties to apply the load at beginning due to limited room space between the beam and floor. Finally we used a door panel to upload the weights while the door panel was hung onto the beam thru coarse metal wire. The weights we used were bags of metal clamps that were borrowed from nearby restoration site (Wuyun Tulou). Each bag was 25kg and total 20 bags were used.

The five data loggers which monitor temperature and humidity at different seasons were also installed at 5 different locations of the building by ASH team (Minoru Ueda).

Huanji Tulou, located in Nanxi Village, Hukeng Town, June 29-30, 2009

Huanjilou was known as the strongest Tulou. It was built in 1693. This tulou has O/D43.2m, 20m in height with 4 floors, 2 rings, 152rooms now housing 21 families, 116 people. It was recorded that in 1918 a R.7 earthquake created a large crack (20cm x 3m) in the wall, but later the gap was sealed up naturally because of its unique circular structure (Figures 13 and 14).

We conducted IRT scan, ultrasonic scan, rebound hammer test, temperature and humidity readings, and dimension measurements. We proposed to use IRT scan to detect the debonding between the earth and wall ribs and thus establish if the self –healing is true or not. However, the crack due to earthquake load is 15 meters high (about 4th floor, close to roof) and access to that area posed as a problem to us at beginning. One option was thru the room where the crack is located. Unfortunately the room was locked and the owner had been working in a city and no key could be found. We also thought to use a skyladder from a fire truck or utility service truck, but the building is located behind other buildings and any trucks could not drive thru narrow footpath. Eventually we hired a construction worker to build a platform using bamboo to that height (Figure 13). The size of crack was measured using laser distance.

Figure 13, Huanji Tulou and Platform

Figure 14, The Reported Crack due to Earchquake

Zhengcheng Tulou, located in Hongkeng Village, Hukeng Town, July 3, 2009

Zhengchenglou was known as the Prince of Tulou. It is the most magnificent round Tulou. Built in 1912, it has an area of 5000m2, 2 rings, 4 floors, and 252 rooms (6 rooms as school classrooms). Outside the circular building resembled a mud-made fort. This Tulou represented by models has been displayed in world architecture exhibition twice because of its beauty in architecture. Zhengcheng was constructed with the Bagua idea (6 room/gua), fire-resistant walls between two guas, 2 wells, stage-like ancestral shrine, representing both north/south China and Chinese/Greek architectural features. There are many cultural treasures such as sculpture, mural paintings, antithetical couplets and work of calligraphy.

We conducted IRT scan, ultrasonic scan, rebound hammer test, and dimension measurements (Figure 15).

5. Help US HISTORY "History, Made for Tomorrow" Crew to Film Hakka Tulou (July 3 -7, 2009)

The HISTORY is creating a new community outreach program "History, Made for Tomorrow" to show case historic places where lessons can be learned to build a sustainable 21 century. Hakka Tulou topic was selected by Dr Libby H. O'Connell, Chief Historian of History Channel.

The PI provided full cooperation with the US History Channel crew to make the History Made for Tomorrow piece on the subject of Hakka Tulou buildings in Fujian Province, China (Figure 16). Liang not only participated in the program in terms of telling story, interview, demonstrating research undertaking at World Heritage Fujian Tulou Site, Yongding, Fujian, China during July 3 -7, 2009, but also provide information on our research being carried out by WVU, review the script and participate in discussions with others on the context where NSF was acknowledged for support to this work.

Figure 15, Testing at Zhengcheng Lou

Figure 16, HISTORY, Made for Tomorrow at Work

6. Laboratory Testing of Rammed Earth Wall Samples

Rammed earth wall samples and wall rib samples collected from field are being further evaluated for their thermo-mechanical properties (Figures 17 and 18). The testing effort includes: 1) compression tests on wall samples for strength and stiffness, 2) evaluation of bond between constituents and wood rib piece/earth thru SEM, 3) CT scanner test for porosity of rammed earth samples if possible, 4) Carbon dating test on wall-ribs, 5) measurement of thermal conductivity of rammed earth samples, and 6) processing of data and documents collected from field studies.

Figure 17, Failed Earth Samples

Figure 18, Wood Rib Samples

7. Development and Submission of Follow-on Proposal to Continue the Research on Hakka Tulou

Hakka Tulou buildings are referred to as the greenest buildings in terms of their planning, sustainable materials (earth and wood), design and construction, landscape, lifestyle, living comfort, agricultural use, resource management, micro industries, renewable energy use, recycling of human and animal waste, and low embodied energy with modest ecological footprint. Thru NSF sponsored present project "SGER: Material and Structural Response of Historic Hakka Rammed Earth Structures", the PIs (Hota and Liang) have investigated the material and structural responses of Tulou buildings that have survived and functioned well under extreme thermal, wind and earthquake-induced loads. A further study on Hakka buildings dated back to 8th century and still being used under the ownership of the same families will reveal Hakka wisdom on sustainability and may have exemplary lessons for our modern world and future sustainable structures, especially in terms of living (thermal) comfort. Some of the sustainability aspects of Hakka buildings are being evaluated by CFC-WVU team.

We would like to develop an extensive research plan to understand the Hakka Tulou construction and its sustainable living in an interdisciplinary manner through multi- college and international collaboration. The PIs coordinated with 10 faculty from College of Engineering and Mineral Resources, Davis College of Agriculture Forestry and Consumer Sciences & Regional Research Institute, all at WVU and Dr Lei of Xiamen University, China and developed EFRI pre-proposal submitted to NSF on Nov 12, 2009, entitled "EFRI- SEED Preliminary Proposal: Planning, Design and Construction of Sustainable Buildings: A Systems Approach" (Proposal# 1008746) while the Letter of Intent (LOI #02116335) was submitted on 10/9/2009.

Part of the proposed effort will research on sustainability concepts embedded in historic Hakka rammed earth buildings (World Heritage) in Fujian province of China by autonomous monitoring the flows and fluxes of energy, heat, water, light, sound, air and occupants thru wireless intelligent sensor network. The data collected will be used for case studies using the proposed energy and water models; the fundamental understandings derived hopefully will unearth a variety of sustainability concepts engaging the above forms of energy or materials, including interactions with nature using Feng Shui principles; and those concepts are expected to be correlated with living comfort of Hakka Tulou buildings such as durable, well lighted, well ventilated, windproof, fireproof, quakeproof, warm in winter and cool in summer.

8. Finite Element Modeling of Tulou Material and Structural Responses

A graduate student is being hired for Spring 2010 to conduct FE modeling of: 1) Load transfer mechanism of earth/rib wall system, 2) Load transfer mechanism of inner wooden structure, 3) Self-healing of crack-after-quake; 4) Thermal comfort of Hakka Tulou building, i.e. warm in winter and cool in summer.

Findings

1. Durability of Tulou Buildings

The outer wall of Hakka Tulou is a rammed earth construction. Specifically, it is built of a composite material known as "Sanhetu" rather than just soil. The Sanhetu is a mixture of red soil, lime, and pebbles. The formulation of Sanhetu is very skill-specific, depending on the type of soil having special bonding characteristics, water content, ratio of re-used soil from old construction to virgin soil, etc. For example, for good bondability, fine sedimentary soil from rice fields after removal of top surface layers of silt is frequently used. Some news articles indicate that soupy glutinous rice and brown sugar are added in some wall systems. This might explain why the earth wall has become so hard with time as in case of Fuxing Tulou. However, when the PIs talked to Tulou residents, they don't agree with that statement.

Durability of Tulou buildings is mainly related to rammed earth wall materials in terms of aging, performance, novel load transfer and binder characteristics. The Tulou buildings selected for study are listed in Table1. They represent a range of Hakka Tulou structures of different ages built in: 1) 8th century; 2) 15th century; 3) 17th century; and 4) 20th century so that the evolution of structural design and construction from 8th to 20th century structures will be evaluated. The wall samples collected from each building during field trip are being scheduled to be viewed using scanning electronic microscopy. We would like to identify and document the compositions (constituent materials) of the rammed earth walls with emphasis on binders. The bond between constituents and wood piece/earth wall ribs will be evaluated thru SEM.

Table 1. Tulou Buildings Studied

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

The PIs observed that there are many types of Tulous, but square Tulou and round Tulou are most common. In Yongding County alone, there are 4,000 square Tulous and 360 round Tulous, plus other types such as half-moon-like, star-like and smaller size ones, there are over 20,000 Tulous in total. Round Tulous were developed as an improvement of square Tulous for better functions. As per local officials, the oldest round Tulou has a history of over 600 yrs. There are about 20 Tulous existing over 600 yrs.

Among the Tulou buildings the team visited, the modes of failures of the rammed earth structures include cracking of walls, erosion or deterioration of wall due to leakage from the roof, damages due to fire, war, and design/construction defects (like Zigzag) etc. The inner wood structure of one round Tulou in Hekeng Village, Nanjing County was burned down but the owner is re-building it while Liben Tulou in Nanxi Village was ruined because of war fire (Figure 19).

Each rammed earth wall was tested nondestructively on-site using Rebound Hammer and Ultrasonic Device and the results are shown in Figures 20-22. The Rebound Hammer used was Model HT 75 manufactured by Tianjing Construction Instrumentation Ltd while Non-Metal Ultrasonic Testing Device was Model NM-4B by Beijing Koncrete. The rebound hammer result indicates that Fuxing Tulou does have the highest strength and hardest but the ultrasonic data don't support. The newest Zhencheng Tulou appears to have good wall strength. Please note that these discussions are for reference and relative comparison only because each building was built locally where the construction materials might vary dramatically and age of building is not the only variable. Limited wall samples are also being tested under compression for strength and stiffness and the results are to be presented in the final report.

Figure 19, Ruin of Liben Tulou

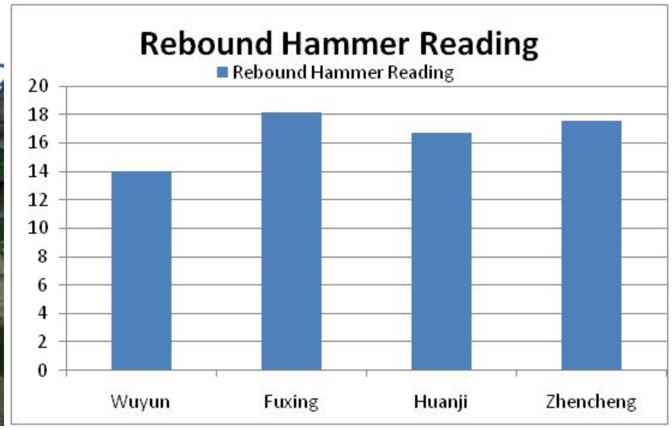

Figure 20, Rebound Hammer Data

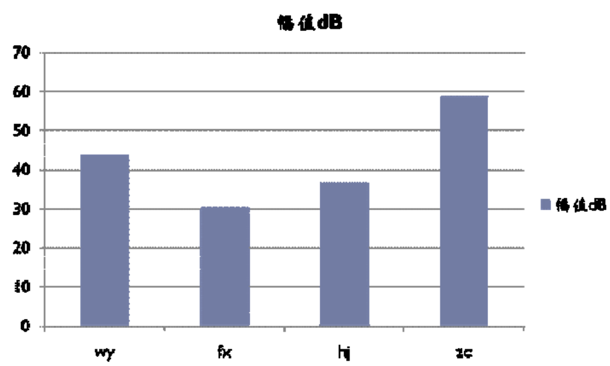

Figure 21, Ultrasonic Amplitude Data

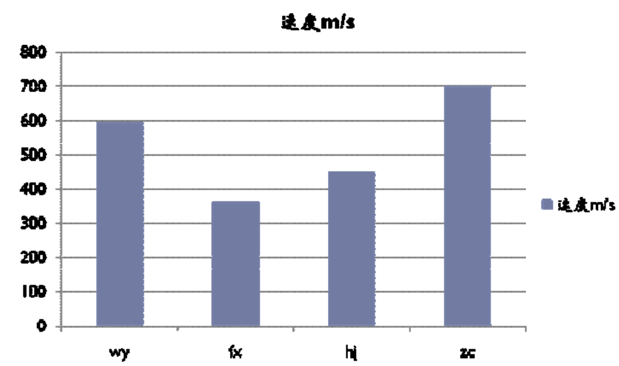

Figure 22, Ultrasonic Speed Data

2. Role of Wall Ribs as Reinforcements

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 inside an eroded rammed earth wall or even from outer wall surface (Figures 23 and 24). They act as reinforcing bars (wall-ribs) in the structures and are placed while the wall is being constructed. This approach is unique and only noted from Hakka earth walls. For that purpose, a pair of special framework boards has to be used. Information was collected from field study and is being used to quantify wall rib density (spacing and size) in a typical Tulou wall construction.

The presence of large amount of wood chips inside the wall might greatly contribute to the earthquake resistance of the structure, and this aspect was planned to be studied through field evaluation using infrared thermography scan camera. However, 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 (Figures 25 and 26). IRT was not applicable to identify if the bond between the earth and wall rib is good or not either. This is because the temperature gradient is not big enough between them, and also because IRT is only able to identify defects under subsurface (at a limited depth). Cold water was spread onto the rammed earth wall with intention to signify the difference in heat transfer rate but was not effective.

Figure 23, Bamboo Chips as Wall Ribs

Figure 24, Wall Ribs on Chengqi Lou

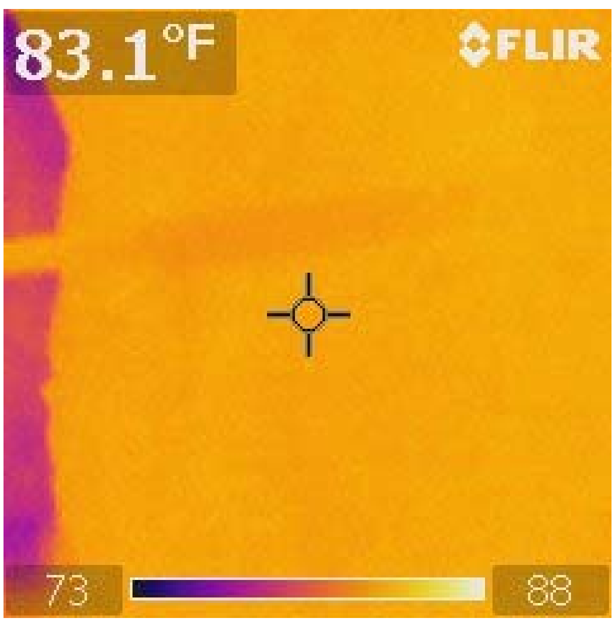

Figure 25, IRT Detects Shadow Wall Rib

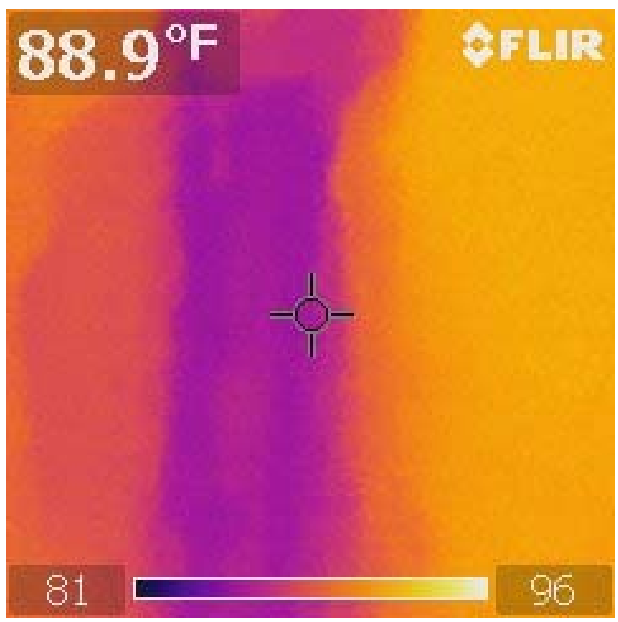

Figure 26, IRT Image of the Wall Crack of Huanji Tulou

Most surprisingly the team found that Huanji Tulou which withstood a strong earthquake with a self-healed crack and was regarded as the strongest building apparently does not have wall ribs inside the wall.

The structural behavior of rammed earth wall including ribs will be simulated through FE analysis to investigate the role of wooden/bamboo pieces in the wall including mechanics of force transfer under extreme loads between constituents and wall rib and their composite action. We will also try if interfacial bond between rib and earth could be identified thru SEM. Some wall rib samples collected from field study are being tested under compression and the results are to be presented in the final report.

3. Structural Integrity of Hakka Buildings

Structural integrity of Hakka Tulou is referring to inner wooden structure rather than outer wall construction. The structural efficiency of Chengqi Tulou building was first evaluated thru load tests during field study and will be further simulated thru FE modeling of force transfer mechanisms. Two types of load tests i.e. roof truss and floor beam were conducted in Chengqi Lou (Figures 27 and 28). First, representative structures were identified for the test; second, a number of strain gages were mounted at appropriate locations; third, strain gages were connected to the multi-channel strain gage indicator; fourth, load was gradually applied and reading from each channel was taken. The geometric dimensions of the building such as column &beam positions, wall thickness, OD/ID etc were also measured. The results are presented in Figures 29 and 30.

Figure 27, Load Test of Roof Truss

Figure 28, Load Test of Floor Beam

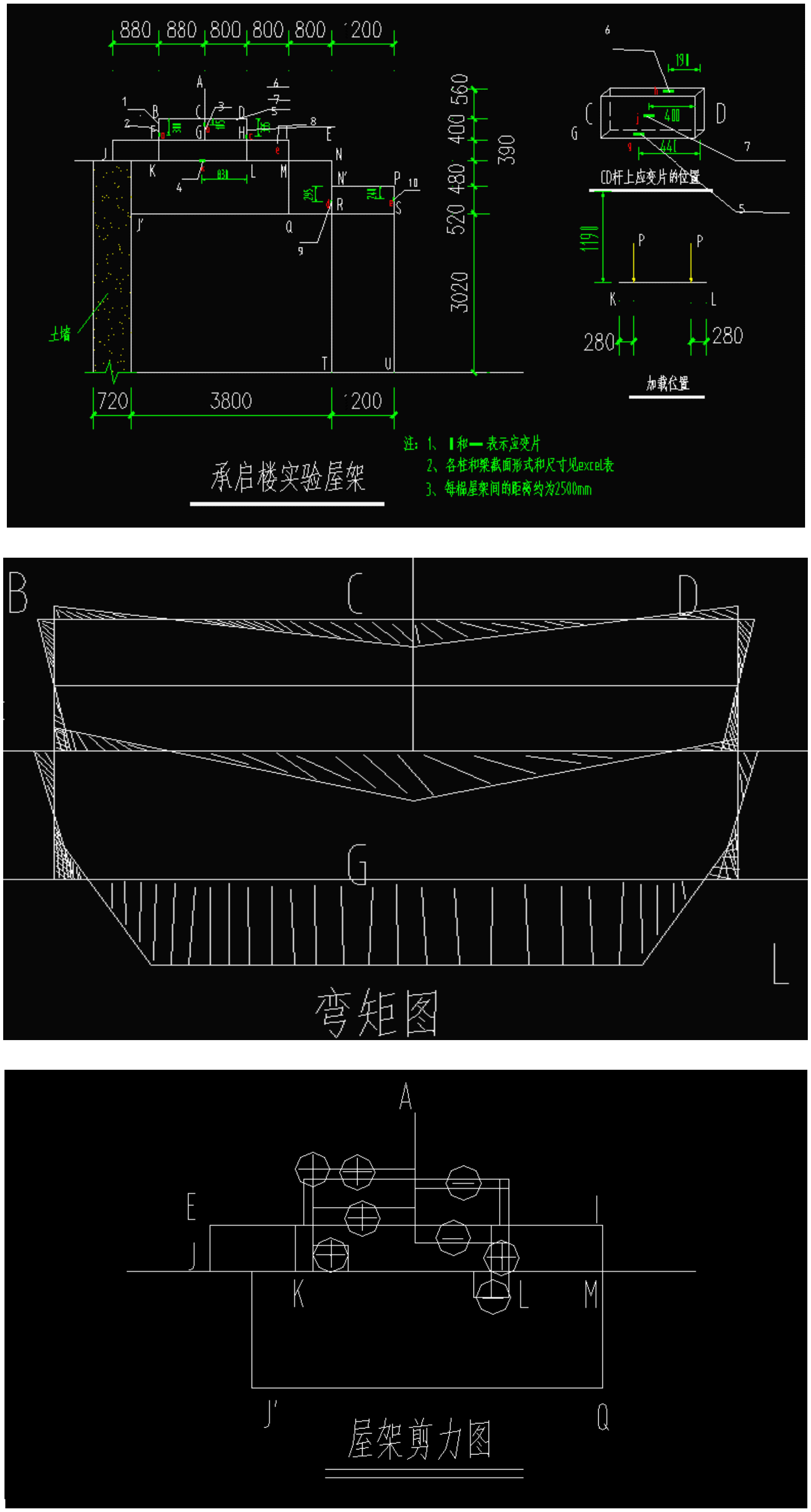

Figure 29, The Set-up, Bending and Shear Diagrams from Roof Truss Load Test

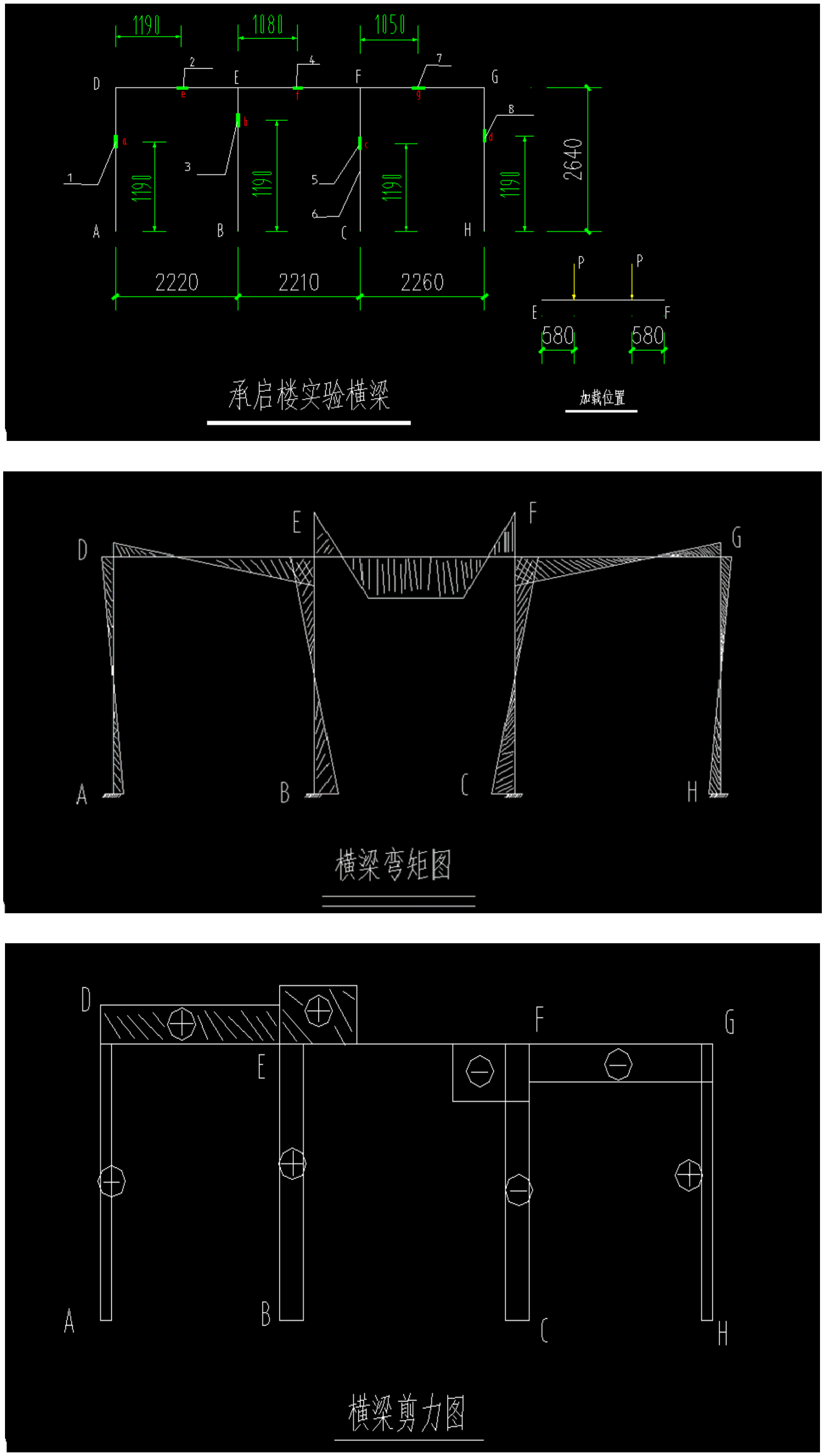

Figure 30, The Set-up, Bending and Shear Diagrams from Floor Beam Load Test

4. Self-healing of Cracks and Earthquake Resistance

Hakka structures have been subjected to extreme stresses induced by typhoons, floods, and earthquakes. Since the 11th century seven earthquakes of above magnitude 5 on the Richter scale have been recorded. Some Tulou buildings have had cracks in their walls and broken roof tiles because of earthquakes; however, there has been no structural damage of any Tulou building.

Huanji Tulou was studied for its earthquake resistance. It was reported that there was a 3m by 20 cm crack 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 Infrared Thermography (IRT) Camera 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. Hence we would verify any self-healing of cracks-after-quake. Unfortunately Huajian Tulou was not reinforced by any wood strips and IRT was found not applicable to identify the debond between wall rib and rammed earth.

The reported crack in Huanji Tulou due to R.7 Earthquake was measured for its width, length & depth during field study. The crack was across-the-thickness (Figures 31 and 32). Based on visual inspection from lintel movement, the crack was not fully recovered, with about 5 cm gap remaining. It is likely the original crack was much larger. We believe that the self-healing capability may be explained on a scientific basis only for small scale cracking. Even for a 20cm crack, as compared to the circumference of a 44 m diameter, it is only 0.14% in strain.

The structural response of Huanji Tulou under earthquake load will be modeled thru FE modeling based on its geometric data collected during field study, using a double ring shell model.

Since the square Tulous have been performing as well as round ones, we suspect if the large mass of outer walls together with the integrity of internal wooden structure is a contributing factor for their excellent performance under earthquake loads.

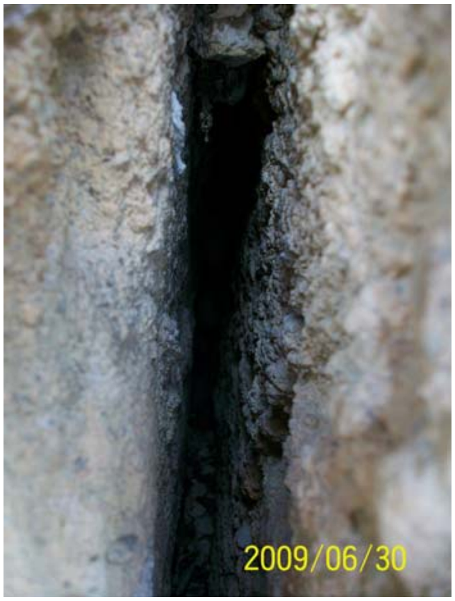

Figure 31, The Crack of Huanji Tulou

Figure 32, The Cavity of Lintel End

5. Energy-efficiency and Thermal Comfort

The high thermal mass of thick outer rammed earth walls means they regulate the internal temperature of a building. If a rammed earth wall is designed into the heating system of a structure, the energy required to both heat and cool the building can be greatly reduced. Rammed earth also naturally regulates the internal relative humidity of the building, producing an improved air quality.

Temperature and relative humidity measurements at various locations around Tulou building were conducted at different times of a day (Figures 33 and 34). The results are shown in Table 2. The inner temperature remained 80F while outside temperature was 112F.

Figure 33, Make a Thermocouple Hole

Figure 34, Digital Thermocouples

We will further identify if Tulou design and its thick wall construction contribute to thermal comfort thru thermo-physical analysis of the structure and heat transfer process analysis of the rammed earth wall using classic Fourier heat conduction equation. Fourier model describes one dimensional steady state heat transfer and near-perfectly applies to the situation of a giant circular structure. . The results will be compared to the above field data. We would like to confirm the effectiveness of a rammed earth wall as a natural air-conditioner if possible, potentially leading to its implementation in modern structural wall systems.

Table 2 Temperature and Humidity Data

Cheng Qi Lou										
Test Date July 1 2009										
1. temperature data (F)										
Time	inner yarc	ring 2 corr	ring 3 corr	gate way	inside roc	inner wall	inner insi	outer insi	outer wall	outer yarc
10:50	80.2	81	84.2	82.8	80.2	81	79.9	81.9	88	82.9
12:00	81.5	82.4	85.5	83.7	79.7	81	79.9	82.2	89	84
13:30	82.4	83.7	86.4	84.9	79.5	83	79.9	82.9	95	89.6
15:20	82.9	84	85.8	85.8	79.5	81	80.1	84.7	112	96.1
18:00	82.6	82.2	84.2	84.9	79.7	80	80.1	90.7	101	96.6
2. humidity data (%)										
Time	inner yarc	ring 2 corr	ring 3 corr	gate way	inside roc	inner wall	inner insi	outer insi	outer wall	outer yarc
10:50	74	72	67	63	78		82	66		71
12:00	74	69	64	62	80		82	65		69
13:30	69	64	58	56	79		82	49		60
15:20	69	64	59	56	79		81	32		53
18:00	69	69	65	58	79		81	38		46

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The PIs appreciated international collaboration with the School of Architecture and Civil Engineering, Xiamen University (XMU), China and ASH-Autonomous & Sustainable Housing Inc, Canada. Dr Ying Lei of XMU participated in the general study tour of Yongding Tulous (June 20 to 23, 2009) and made the Hakka Tulou Forum (June 24, 2009) a great success. Dr Lei sent his technician Yanhao Li and graduate student Yongqiang Jiang to work with Dr Liang to conduct the entire planed field studies (June 26- July 3, 2009). The XMU team also conducted testing of some samples collected from field for their mechanical properties. Mr. Jorg Ostrowski of ASH reviewed the plan of field study and made many comments prior to field trip. ASH team consisting of Jorg Ostrowski, Helen Ostrowski, Minoru Ueda, and Yuan Lee contributed much to the success of the Hakka Tulou Forum and (except Minoru Ueda) also participated in the general study tour of Yongding Tulous.

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