

## **NONDESTRUCTIVE EVALUATION OF HISTORIC HAKKA RAMMED EARTH STRUCTURES**

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

**Keywords:** Hakka Tulou, rammed earth, earth structures, load test, load sharing, thermal comfort, NDE, nondestructive evaluation, ultrasonic, rebound hammer, Infrared thermography

### **1 INTRODUCTION**

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

Hakka rammed earth buildings (also known as Tulou), in the Fujian Province of China, reflect the emergence of innovation, evolution, and advancement in the engineering of rammed earth construction from the 8th to 20th centuries. Those earth buildings have thick (~2m) outer rammed earth walls and inner wooden structures making up floors and rooms, are three to five stories in height, round or square in shape, and have hundreds of rooms housing up to 800 people. Since 1980s, thousands of visitors (including professionals and scholars) have visited Hakka earth buildings, resulting in many illustrative photographs and travel logs about Tulou's characteristics, architecture including defense devices and fire walls, and construction techniques. It is worth noting that Aaberg, a Danish architect, visited Hakka earth buildings in 1997 and reported the architecture marvel of those structures (Aaberg, 2000). More recently, Ostrowski, a Canadian architect has been researching ecological footprint of Hakka earth buildings which are considered "green" in terms of their planning, design, construction, lifestyle, resource management, renewable energy, and modest ecological footprint (Ostrowski et

al, 2007). However, people have underestimated the engineering value of those buildings in terms of low energy consumption for comfortable living, sustainability, and durability (Liang et al, 2009).

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

Table 1: Hakka earth buildings studied

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

## 2 NONDESTRUCTIVE EVALUATION OF RAMMED EARTH WALLS

Nondestructive evaluation (NDE) techniques refer to those methods that enable the testing of materials/ structural components without impairing their future usefulness or the testing and long-term monitoring of in-situ structures (Halabe et al, 1995). Because of the nature of the present study, NDE testing was necessary as to be able to assess the conditions of the rammed earth walls, without damaging the historic structures. Both an ultrasonic testing device and rebound hammer were employed to field-evaluate the wall systems and collect data to better understand the durability and structural integrity of rammed earth walls in a comparative manner. In addition, Infrared Thermography Scanning Camera was also used with intention to detect the bonding status between earth and wall rib, while thermal couples and data loggers were used to collect temperature and humidity data to be discussed in Section 4.

### 2.1 Ultrasonic Method

Ultrasonic testing is a NDE test which can tell us the strength of the material as well as if defects are present in the material. A wave, in this case produced by an ultrasonic transducer, will travel through a material such as the rammed earth wall and be detected by a receiver (as shown in Figure 1). The way how the wave propagates can give valuable information with respect to the structural integrity of the structure being tested. More specifically, the velocity of the wave is a function of the material's properties such as stiffness, density, and Poisson's ratio as well as the presence of defects. Similarly, the amplitude of the wave sent through a material is expected to be higher through a more "sound" material or a material that shows fewer defects. A combination of velocity and amplitude measurements provides more useful information by increasing the sensitivity of the ultrasonic technique to defects. In most cases a decrease in wave amplitude represents a possible defect. One can compare the velocity of a wave to the amplitude to see if there are inconsistencies. If inconsistencies exist then there is a possibility that a defect may be present (Halabe et al, 1995).

Figures 2 and 3 show the ultrasonic velocity and amplitude results for the buildings tested. Both charts are consistent and show the same trend. This most likely means that no large defect exists in the areas of the material that were tested and that the readings may reflect the strength of the materials. Note that each data point represents an average of 25 to 30 measurements. As can be seen in Figs 2 and 3, apparently, there is no direct correlation between the age of the Tulou structures and the velocity/amplitude (the strength of the rammed earth walls) of the ultrasonic wave. Other than the age, there are many more parameters in the wall

system varying from one Tulou to another, including different earth constituents, with or without wall ribs, and varying construction quality.

A useful discussion on these NDE data can be made with reference to the mechanical properties and other testing results of the rammed earth wall samples that were generated in the laboratory (Liang et al, 2011). Ultrasonic data indicate Zhencheng earth wall has the highest strength. This observation is generally supported by the SEM and static test results. Wuyun has higher velocity than Fuxing and Huanji. Huanji Tulou earth sample is brittle and the researchers were not able to prepare any specimens of a regular shape. Thus, Huanji Tulou earth sample would have the lowest strength among the buildings studied. Contradictorily, Fuxing Tulou earth sample has been proven strong and hard. Its lowest ultrasonic velocity should be attributed to the fact that all the measurements from Fuxing were conducted on wet walls because of raining weather during field study and the earth wall might have become soft. Having the above points in mind, the Ultrasonic testing result does agree with the mechanical properties of the earth wall samples



Fig 1: Ultrasonic testing heads and device

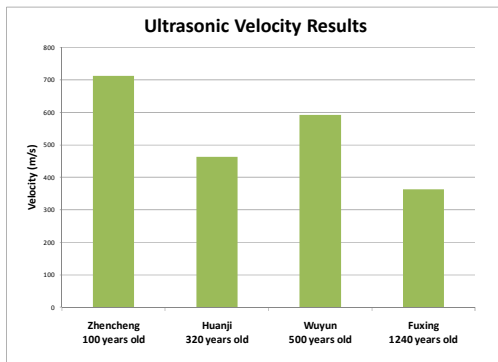


Fig 2: Ultrasonic velocity results\*

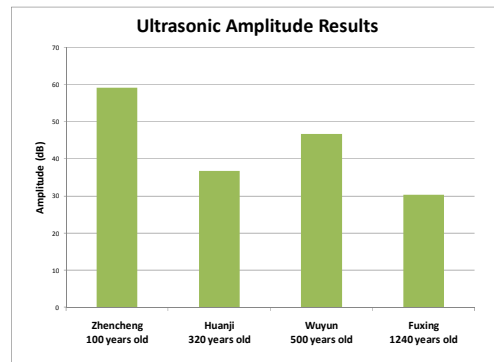


Fig 3: Ultrasonic amplitude results\*

\*Fuxing Tulou data obtained on wet walls due to rain

## 2.2 Rebound Hammer Method

As per ASTM C805, a rebound hammer works as follows: A steel hammer impacts, with a predetermined amount of energy, a steel plunger in contact with a surface of concrete, and the distance that the hammer rebounds is measured. This is shown in Figure 4. During the field study, two types of rebound hammers were used, one specifically for brick and another specifically for mortar. Figure 5 shows the results of the rebound hammer test. Note that Rebound Hammer is not designed for rammed earth wall but offers a method to quantitatively evaluate the strength of Tulou earth walls. Each data point represents an average of 32 to 64 readings in case of rebound hammer measurement. Also, all the measurements from Fuxing were conducted on wet walls because of raining weather during field study and its value was likely underestimated. In a similar

manner dealing with the ultrasonic data, the discussion on the rebound number can be made with reference to the strength and modulus data of the rammed earth wall samples reported in the paper by Liang et al (2011).



Fig 4: Rebound Hammer

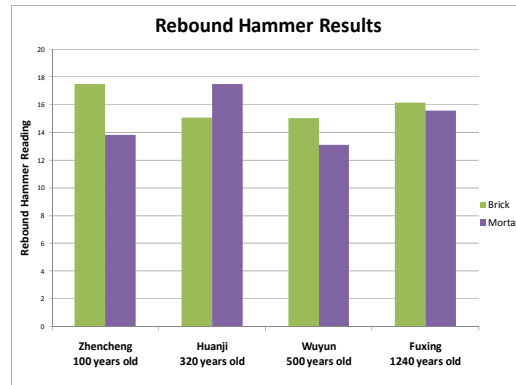


Fig 5: Rebound Hammer results

\*Fuxing Tulou data obtained on wet walls due to rain

As shown in Figure 5, the average rebound hammer readings do not show any correlation between age of the Tulou and hardness of the material tested. Apparently, the brick rebound hammer represents the conditions of the rammed earth wall more accurately than the mortar rebound hammer with reference to the experimental modulus data of the rammed earth walls. According to the brick rebound hammer values, the Zhencheng would have the highest modulus of the elasticity, followed by Fuxing, and the Wuyun and Huanji would have similar low modulus values. Except for Huanji where the mortar rebound hammer average reading was much higher than the brick rebound hammer, for other Tulou, the brick rebound hammer always gave higher average reading than the mortar rebound hammer. Note that each value is a statistical average over a number of measurements.

For the purpose of this project, nondestructive testing using ultrasonic or rebound hammer should effectively tell us a quantitative comparison of the strength of rammed earth walls between the different Tulou tested. However, without a calibration chart of the ultrasonic device/rebound hammer for the rammed earth wall, these tests were not able to yield material strength values to be compared to those values determined from material tests (Liang et al, 2011). Instead, a comparison of NDE data with experimentally determined strength data of the rammed earth walls, would establish the confidence for further wide use of such NDE techniques.

Both types of NDE data do not reveal a direct correlation between the strength of the rammed earth walls and the age of the structures. Other than the age, each rammed earth wall was constructed using resources locally and preparing the wall materials differently. The deterioration rate of each wall with increased exposure to the environments and other aging factors would be different, pending on the quality of the rammed earth wall construction. For example, Fuxing Tulou is at an age of 1240 years but its rammed earth wall retained strength higher than those of the Wuyun Tulou which is 500 years old and Zhenzheng Tulou which is 100 years old. What is remarkable of this characteristic is that at such old age one would be surprised to find a local domestic material be able to retain such strength. This situation however raises more questions as some earth walls were reinforced with bamboo or wood sticks that also have a serious impact on the strength of the rammed earth wall. Overall these rammed earth walls are amazingly strong and hard. The rammed earth wall of such level of hardness even broke two lock rings on a new hammer drill while making a 3/8" hole in order to place a thermal couple close to the center of Chengqi Tulou wall during field study.

### 2.3 Infrared Thermography Scanning Method

Infrared thermography (IRT) is a viable NDE method potentially capable of scanning a large area of testing structure and detecting subsurface delaminations and debonding between the surface layer and the substrate. This technique is based on the principle that subsurface defects and delaminations affect the overall thermal conductivity of the material, leading to different rates of heat transfer through sound and defective regions and thus, surface temperature differentials. For the present study, a brand new portable IRT camera model InfraCAM SD Camera was purchased (shown in Figure 6) and brought to China for field studies.



Fig 6: Portable IRT camera used

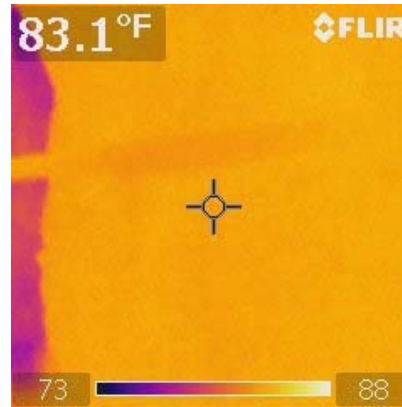


Fig 7: IRT detecting shallow wall rib

IRT camera was intended to perform a couple of functions upon verification of its usefulness during field study. One function would be to identify the presence of a wall rib with reference to a wall without wall ribs. If successful, we would be able to quantify the spacing, pattern, size and total volume of wood or bamboo wall ribs used as reinforcement within the rammed earth walls. Unfortunately, it was found that the IRT was not sensitive enough to detect the difference in the heat transfer rate between the walls with or without wall ribs. This is because the constituent materials to build a rammed wall, including earth, wood, bamboo, stone and others are all natural materials. Under a normal condition, they are all thermally in equilibrium. The surface temperature difference between the walls with or without wall ribs is almost zero, especially when the wall ribs are embedded in depth away from the wall surface and the wall has a thickness of 1.5 to 2 meter. Note that IRT is only able to identify defects under subsurface (at a limited depth). For example, the IRT is indeed able to detect the wall rib as shown in Figure 7 where a slightly dark shadow represents the wall rib, when the wall is around 12" in thickness with a crack in the vicinity. Due to crack, wind effects and shallow embedment of the rib in the wall, the temperature difference between the wall rib embedding area and its surrounding just meet the camera's sensitivity (~0.5C).

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

A third intention was to use IRT camera to verify if there was any self-healing response of a crack-after-quake from Huanji Tulou as discussed in depth in (Liang et al, 2011). Unfortunately it was found during field study that Huajian Tulou was not reinforced by any wood strips and IRT was found not sensitive to identify the debond between wall rib and rammed earth. Hence, no positive results were generated from the IRT camera.

### 3 STRUCTURAL EVALUATION OF FLOOR AND ROOF SYSTEMS

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

#### 3.1 Full Scale Floor System Testing

The floor system of a Tulou building consists of a number of columns, beams and floor panels (Figure 8). Each load carrying member is jointed to each other through pinned connection. All horizontal beams are connected around the inner yard to make a circle. The focus of this set of load testing is to better understand how the floor member responds to an external load and how the load is distributed among the neighboring members.



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

The floor system of Chengqi Tulou was tested by means of a two point load of up to 550 lbs. The test section of the floor is shown in Figures 8 along with a schematic illustration where each member is assigned with a number (M1 to M7) and strain gage locations are indicated. The load was applied onto Beam M6 between Column M2 and Column M3 as two equal concentrated loads symmetrically placed.

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

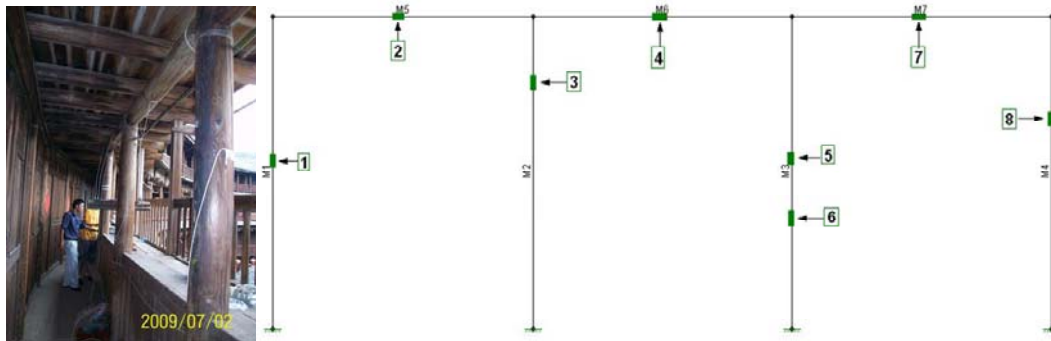


Fig 8: Load testing of floor system, member definition and strain gage locations

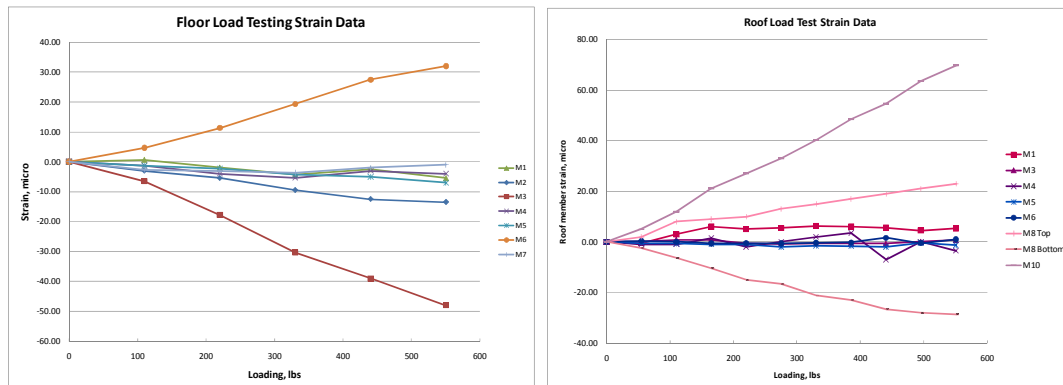


Fig 9: Strain data from load testing, a) floor system member strain data and b) roof truss member strain data

The strain data generated from the floor testing are graphically shown in Figure 9a, in terms of the strain gage locations and corresponding structural members as defined in Figure 8. The strain was recorded as a function of loadings for each member. Each strain value at a given loading was an average of three measurements from three separate runs. The load applying member M6 (gage #4) behaved as expected and gave a strain of 32 microstrain under maximal loading of 550 lbs. All other members had small strain values except the vertical member M3 (gage #5) that had unusual much higher values and gave a strain of 48 microstrain under 550 lbs.

### 3.2 Full Scale Roof Truss Testing

The roof truss structure is much more complicated as compared to the floor system and is shown in Figure 10. 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 10 shows a photo of the major sections of the roof truss structure being evaluated while the entire roof truss structure is schematically illustrated where each member is assigned with a number (M1 to M14) and strain gage locations are indicated with reference to mounting member. More specifically, the load was applied onto Beam M10 between Columns M3 and M4.

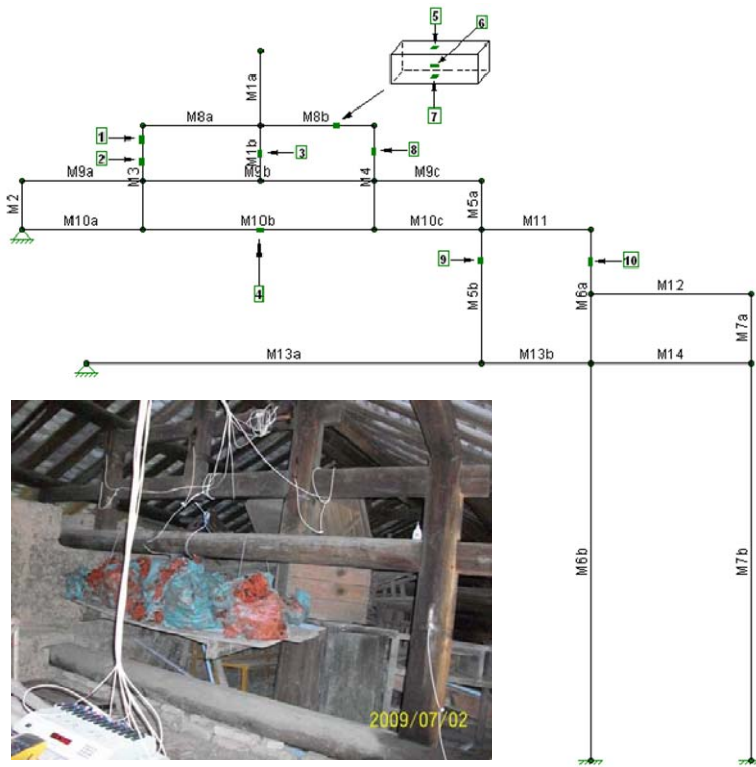


Fig 10: Load testing of Tulou roof truss, truss member definition and strain gage locations

The strain data generated from the roof truss structure testing are graphically shown in Figure 9b, as per the strain gage locations and corresponding structural members as defined in Figure 10. Similarly, the strain value was recorded as a function of loadings for each member mounted with strain gage. Each strain value at a given loading was an average of three measurements from three separate runs except that Member M4 (gage #8) had only two sets of data to average while the third set of data were mostly positive, resulting in uncertain trend for Member M4. It is not sure if this unclear trend was attributed to disturbance during testing or structural sensitivity. Note that the strain gages used were all 5 cm long gages to maximize the ability of detecting any small strains. All other members except M4 behaved as expected. The load applying member M10 (gage #4) gave a strain of 70 microstrain under maximal loading of 550 lbs. For M8, the bottom side was subjected to compression (negative strain) and the strain values were closely matching those of the top tension side.

### 3.3 Load Sharing Effects of Floor and Roof Truss Systems

The load testing of both the wooden floor and roof truss systems resulted in small strains in members with the max strain about 32 microstrain from the floor test and about 70 microstrain from the roof test at a loading of 550 lbs. The access space available limited to apply additional loads. Caution was applied not to generate disturbance while conducting test. Fortunately, strain responses from major loading members appeared to give

meaningful trends. The results show that both the wooden roof truss and floor system are structurally sound even with the high age of the structure. From FE analysis (Stanislowski, 2011), for the floor system a modulus of elasticity of 1.85 msi would match the field test strain results well (i.e. 32 microstrain on the load applying member) while for the roof truss a modulus of elasticity of 0.85 msi would match the roof load test results closely (70 microstrain on the load applying member). The difference in stiffness between the roof truss and floor system could be a number of factors.

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

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

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

#### **4 THERMAL COMFORT ANALYSIS OF LIVING IN HAKKA TULO**

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

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



In order to illustrate how effective the use of high thermal mass has been implemented in the Hakka Tulou, temperature and humidity data were recorded. During July 1, 2009, temperature and humidity readings were recorded at Chengqi Tulou by West Virginia University and are shown in Tables 2 and 3. Seven day period temperature and humidity data obtained using Data Loggers at Chengqi Tulou from June 29 to July 6, 2009 were presented by Ueda (2011).

Table 2: Temperature data of Chengqi Tulou (Field collected July 1, 2009)

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

Table 3: Humidity data of Chengqi Tulou (Field collected July 1, 2009)

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

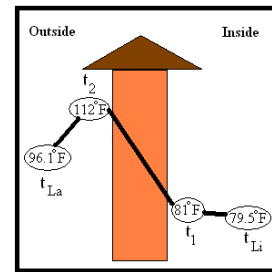


Fig 11: Chengqi Tulou temp profile

Table 2 shows temperatures recorded at different locations at the Chengqi Tulou, i.e. outside the Tulou, the outer and inner rammed earth wall surfaces, and inside an interior room. As can be seen from Table 2, the hottest that the outer surface of the rammed earth wall ever reached was 112° F with a temperature profile inside and outside Tulou shown in Figure 11. Since this is the most extreme temperature difference, this set of temperatures from 15:20 can be used to calculate the thermal resistivity in situ, giving a thermal resistivity of 1.0986 m.K/W (Stanislawski, 2011).

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

Hakka Tulou have no insulation from their rammed earth walls and instead must rely on the high thermal mass that rammed earth provides. Materials that have a high density such as concrete and rammed earth require more heat energy to change their temperature while materials with low density such as wood do not need a lot of heat energy in order to change temperatures. A successful application of thermal mass is one in which internal temperatures of a structure are kept stable when compared to varying temperatures from the outside. For

example, during the warm summer season a material with high thermal mass should absorb the heat from the outside while keeping the interior cool during the day. At night the material with high thermal mass should release the heat to keep the interior temperature stable when compared to the colder night temperatures outside. During the winter the material with high thermal mass should be heated by direct sunlight in order to release heat and keep the interior temperatures at a comfortable level (Reardon et al, 2008). These thermal comfort benefits have also been observed in cave dwelling (Watanabe, 2003). Seven day period climate data (Ueda, 2011) clearly show that while temperature or humidity fluctuates outside, the interior temperature or humidity remains constant at a comfortable level throughout the entire week. As observed from WVU and Ueda data, the thermal comfort zone is achieved due to the effective use of thermal mass from the rammed earth walls.

## 5 CONCLUSIONS

Through this study we have investigated five in-service Hakka rammed earth structures, i.e. Fujian Tulou of China, in terms of their material and structural responses under thermal and mechanical loads. All field studies were conducted in a nondestructive manner using techniques such as infrared thermography, rebound hammer, ultrasonic testing, thermocouples, load tests on roof trusses and floors. The results show that NDE techniques such as ultrasonic and rebound hammer were proved effective to quantitatively compare the strength of rammed earth walls, while Infrared thermography was found not sensitive enough to detect the presence of wall ribs. The full scale load testing result and structural analyses conclude that both the floor and roof truss systems are structurally sound and the jointed neighboring members have a high load-sharing effect with the load-carrying beam. The Hakka people found ways to live in thermal comfort without the need of mechanical heating in winter or cooling in summer due to their effective use of rammed earth construction. This was done without the use of insulation, which would help better maintain heat within the structure during the winter seasons. Modern construction can simulate the Hakka construction techniques and make rammed earth construction a viable building material option of the future.

## ACKNOWLEDGEMENTS

This study was supported by NSF-US (CMMI #0908199). The PI (Liang) would like to thank the following for assistance during field study: Local and County Government Officials of Yongding, Fujian; J Ostrowski and his ASH team; Minoru Ueda of MU Design; and many individuals including officers from Tulou Administrations, and Owners of Hakka Tulou studied.

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