International Workshop on Rammed Earth Materials and Sustainable Structures & Hakka Tulou Forum 2011: Structures of Sustainability

Nondestructive Evaluation of Historic Hakka Rammed Earth Structures

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Acknowledgment and Disclaimer

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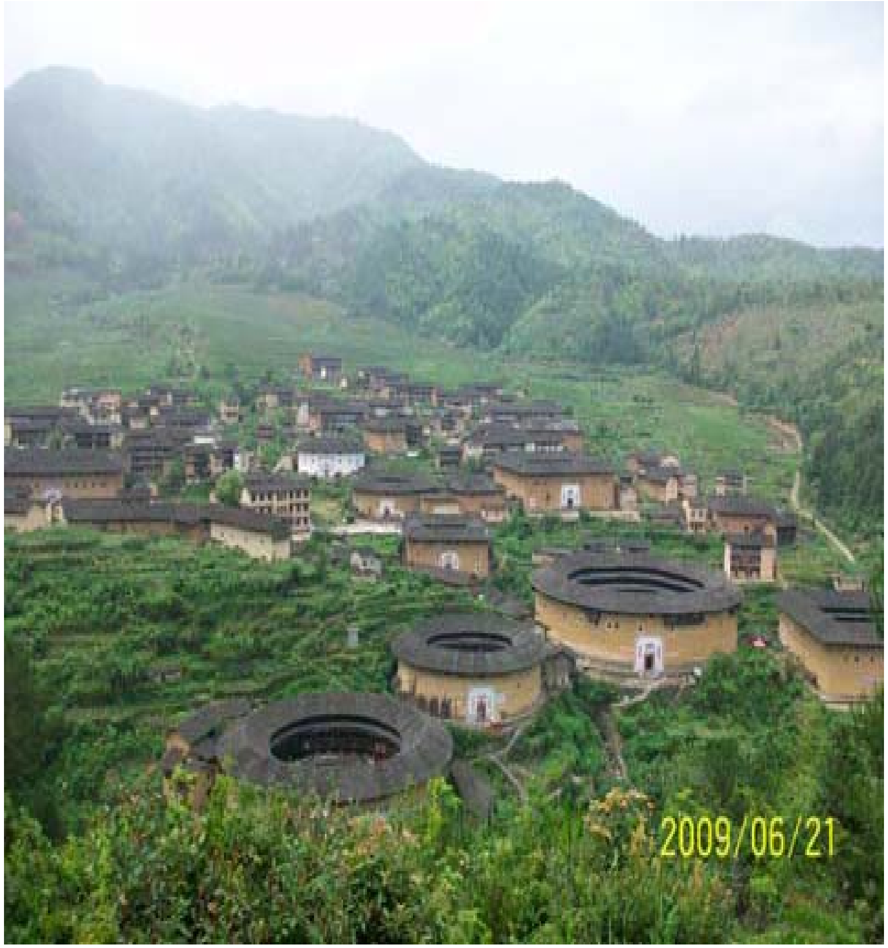
Hakka Tulou

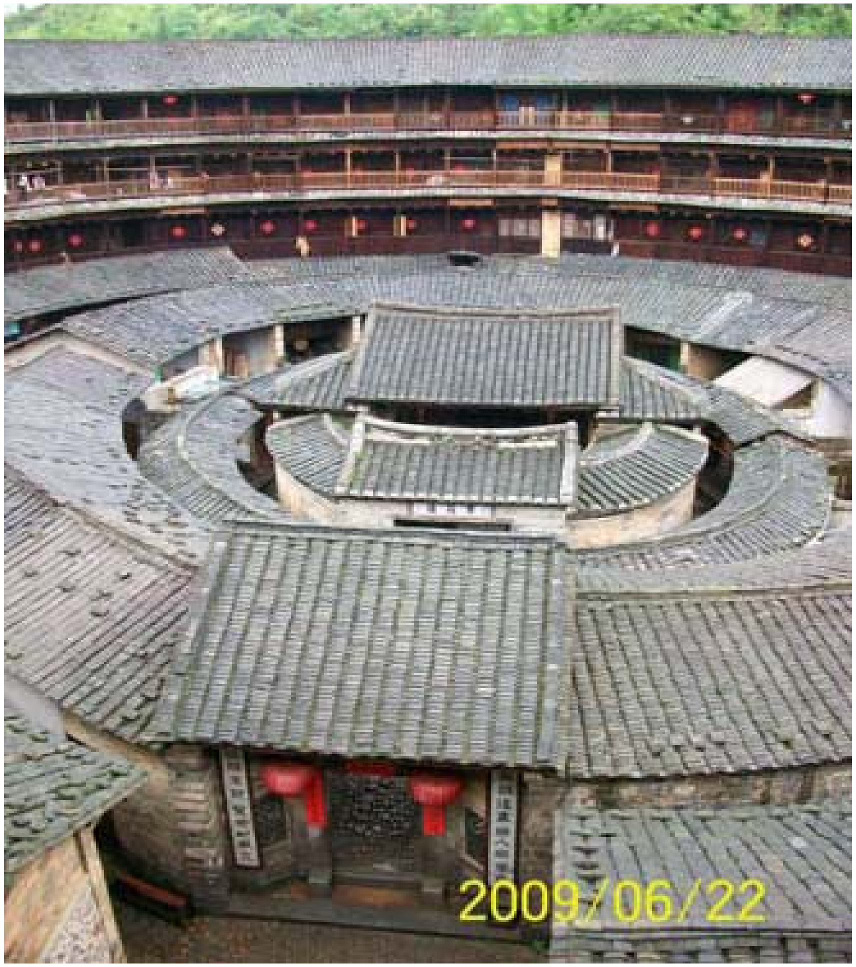
- WHAT:
  - Rammed earth dwellings
  - Up to 800 people capacity
  - ‘Green’ energy efficient
  - 1,000-5,000 m^2
  - Square or circle in shape
  - UNESCO world heritage
- WHEN:
  - Built from 10^{th} to 20^{th} centuries
- WHERE:
  - Fujian Province of China



Objectives of the Study

To better understand the thermo-mechanical and aging responses of Hakka Tulou under thermal and earthquake loads through

- Nondestructive field evaluation including load tests
- Laboratory testing of field samples and
- Finite element modeling.



The Scope of Work Conducted

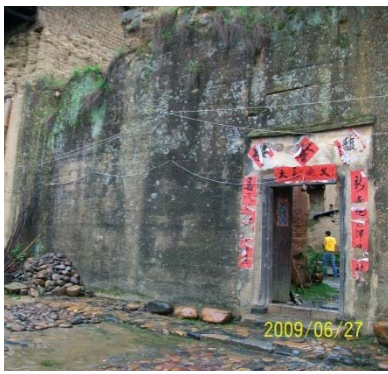
- Thermal and Mechanical Responses of Hakka Tulou Rammed Earth Structures
  - Hakka Tulou Forum 2009
  - Hakka Tulou Forum 2011
  - Field Study
    - Selection of Tulous for Study
    - Samples Collection → Earth/Wood Characterization
    - Earth Wall Durability
      - In-situ Strength Test
        - Ultrasonic
        - Rebound Hammer
      - Earth/Wall Rib Bond
        - Infrared Thermography
        - Vol. Fraction of Wall Ribs
      - Earthquake Resistance
        - Self-healing of Crack?
        - Failure Modes
    - Structural Integrity
      - Floor System Load Test
      - Roof Truss Load Test
    - Energy-Efficiency
      - Thermal Data
  - Campus Study
    - Earth/Wood Characterization
      - Carbon Dating
      - SEM-EDS
      - Tension Compression
    - Field Data Processing
    - Finite Element Modeling
      - Floor/Roof Responses
      - Self-Healing
      - Crack Formation
      - Earthquake Resistance
    - Thermal Comfort Analysis

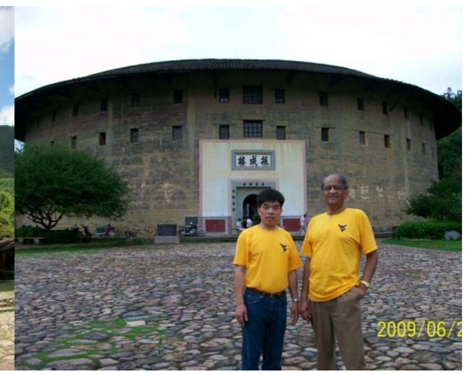
Team at Zhencheng Tulou: Z Zhang, J Ostrowski, R Liang, G Hota, Y Lei, Y Lee, H Ostrowski, M Lu

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

List of Tulou Studied

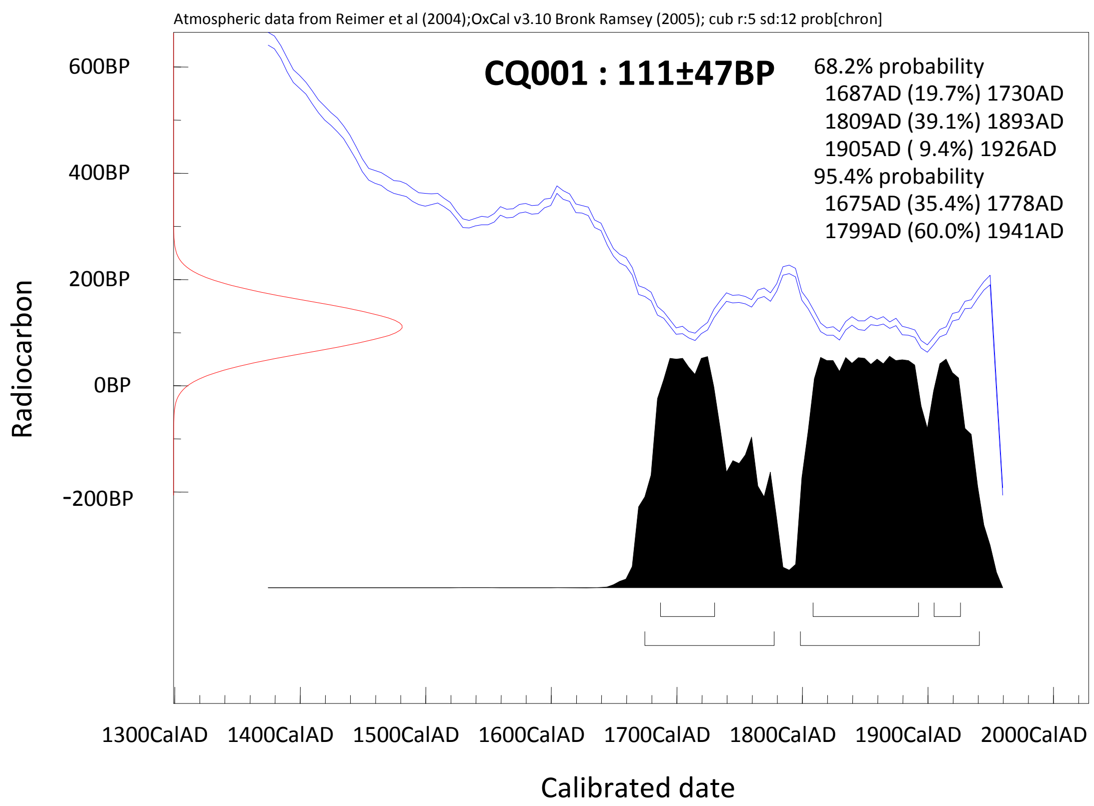
Title of Tulou	Shape	No. Storey	Age	Status
Fuxing Tulou	Square	2 storey	over 1200 years	partially in service
Wuyun Tulou	Square	4 storey	over 500 years	partially in service
Chengqi Tulou	Round	4 storey	over 300 years	in service
Huanji Tulou	Round	4 storey	over 300 years	in service
Zhencheng Tulou	Round	4 storey	about 100 years	in service





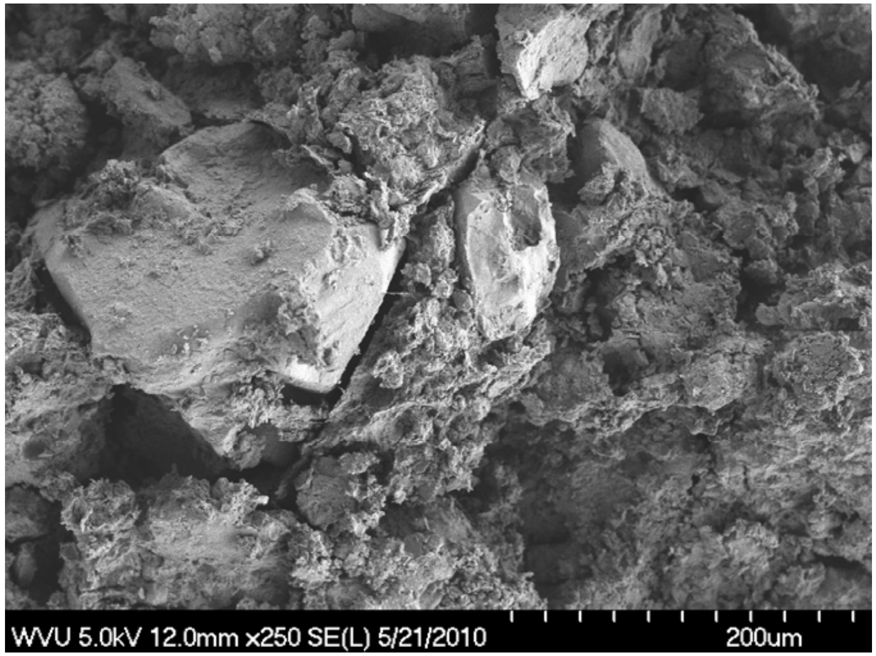
Validating Age of Samples: Carbon Dating Age of Chengqi Tulou

- Wooden sample from Chenqi Tulou sent for Carbon Dating.
- Built from 1662-1709 as per records.
- Results show that this statement is conclusive.
- Age of other samples can therefore be assumed accurate.



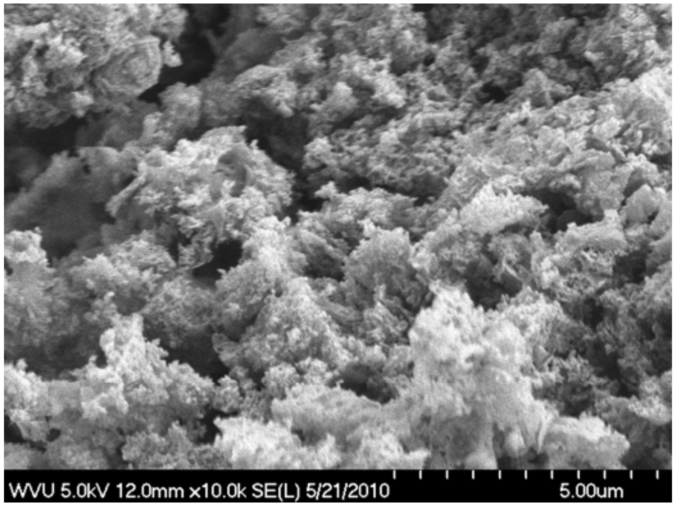
SEM Analysis of Rammed Earth Samples

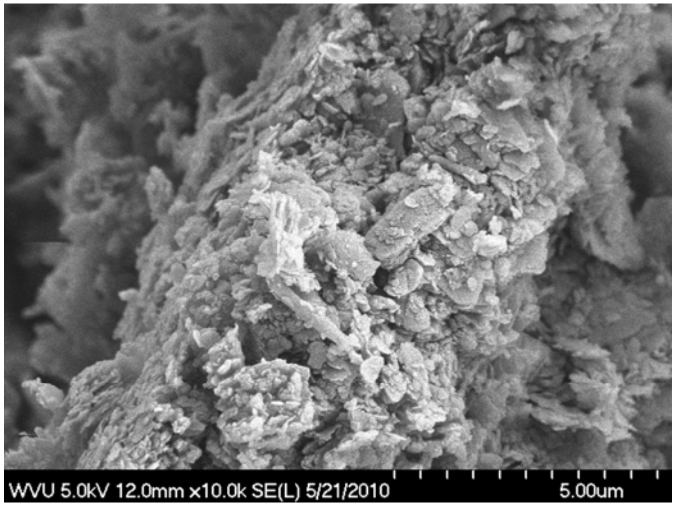
- SEM-Scanning Electron Microscope
  - To examine RE samples at a micro scale
  - To reveal their compositions/constituents
- Allows one to observe and compare their morphology of various RE samples



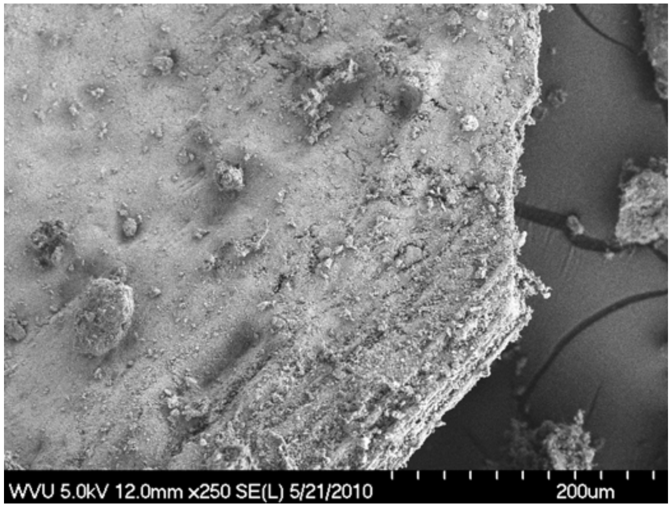
Zhengcheng Tulou earth sample SEM image showing stone/rocks

SEM Images





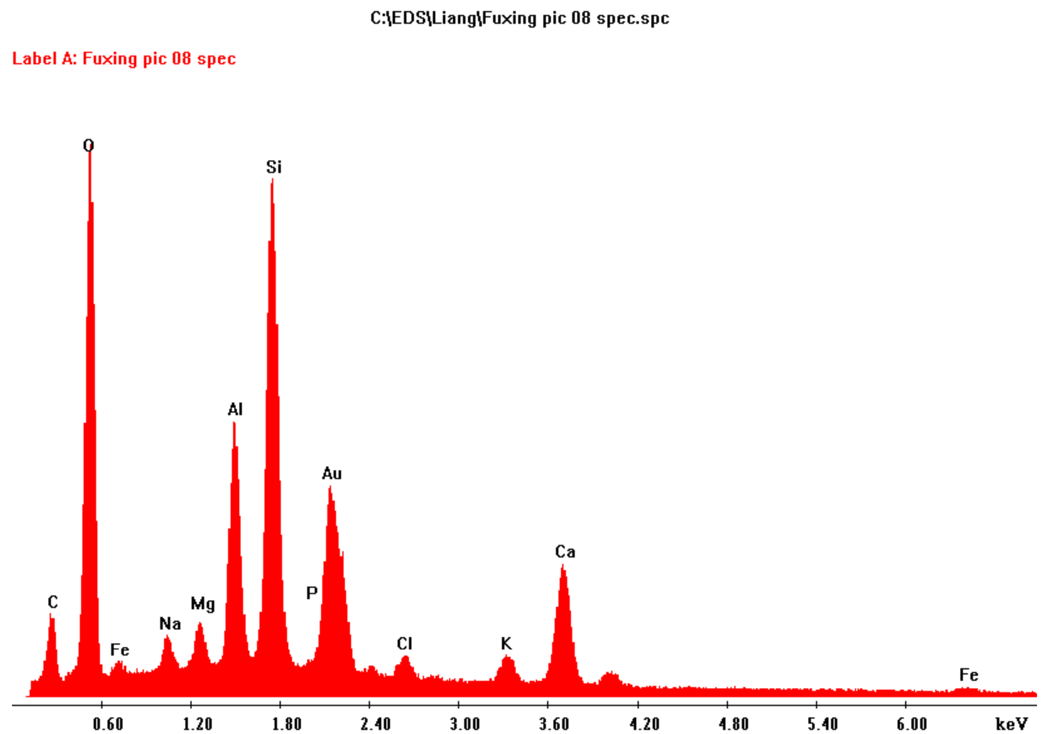
Fuxing Tulou (Left) and Chengqi Tulou (Right) Earth Sample SEM Images



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

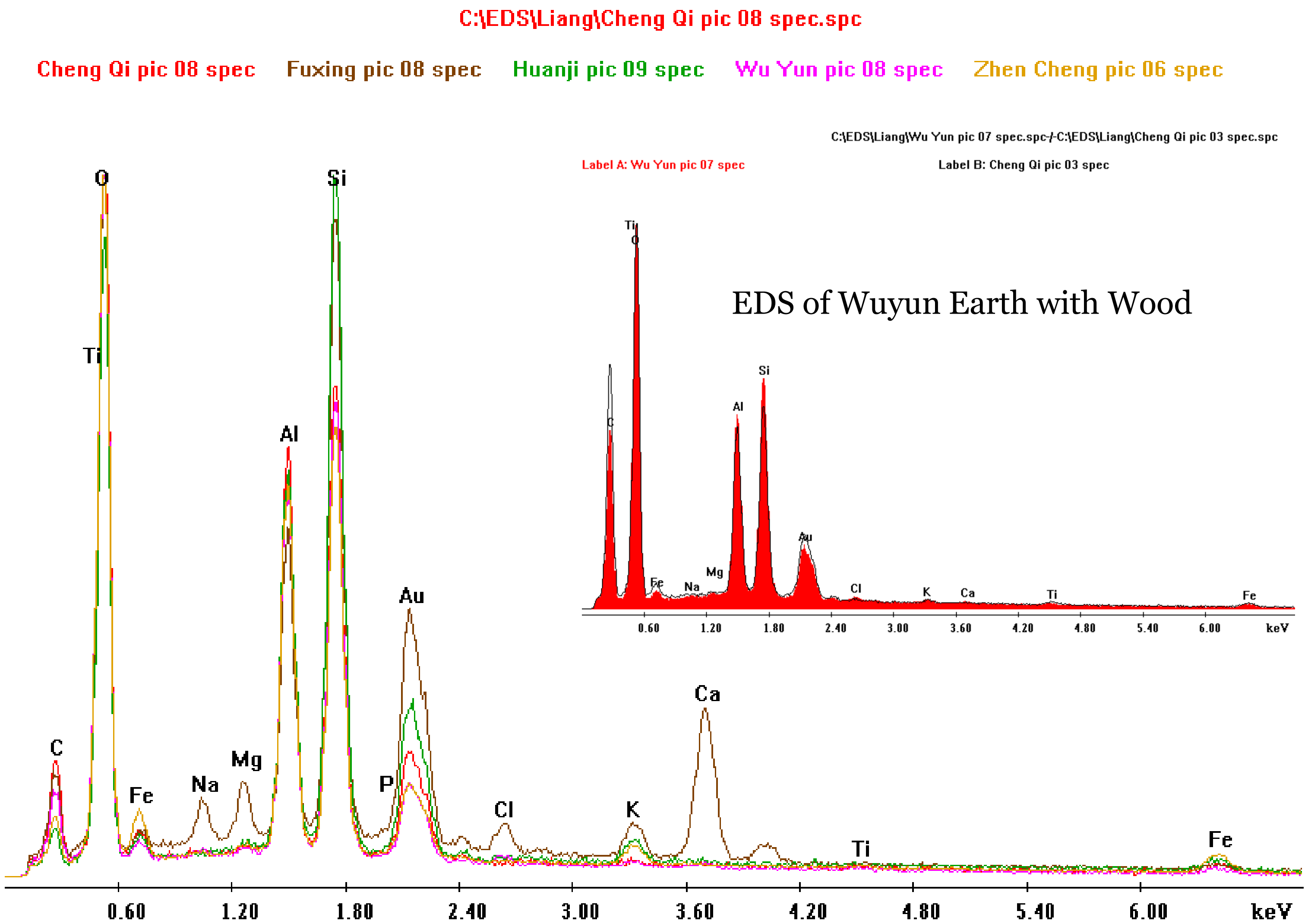
EDS Analysis of Rammed Earth Samples

- EDS-Energy-Dispersive X-ray Spectroscopy
  - To determine the chemical composition of a sample by showing the amount of existing elements relatively to each other.
- Allows one to compare composition of rammed earth samples from different locations



Fuxing RE sample EDS chart showing rich calcium content

EDS Comparison of Five Tulou RE Samples



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

- All samples show an abundance of oxygen, silicon, and aluminum
- Zhencheng, Chengqi, and Wuyun, show an abundance in titanium
- Chengqi and Wuyun also show significant amounts of carbon, due to the presence of wood pieces
- Fuxing shows abundance of Calcium, key element in lime
- Results show that composition of rammed earth is unique to local environments of the Tulou

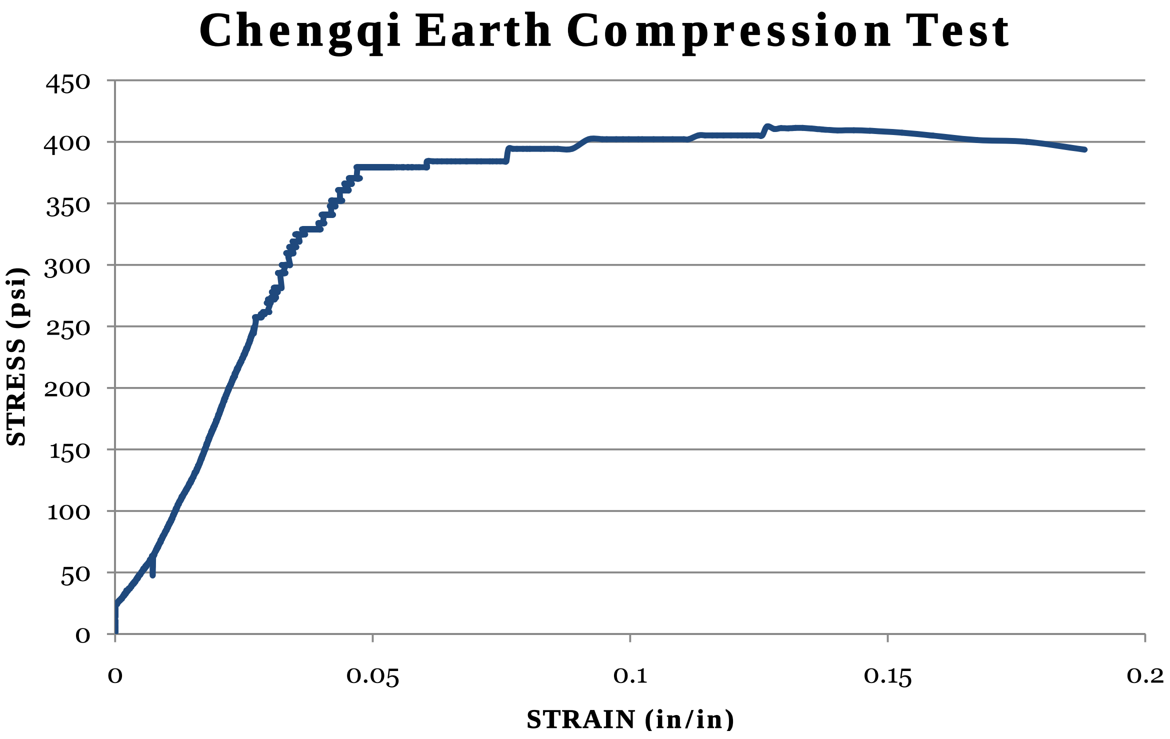
Material Testing of Earth and Wood Samples

- Field collected samples include: rammed earth, reinforcing wood and bamboo, as well as structural wood from internal wooden structure.
- Wooden stick, bark, and/or bamboo strip were used for reinforcing rammed earth walls at most Tulou sites.
- RE samples very difficult to extract, thus sizes are not to ASTM standard.
- Tests performed on Instron Testing instrument at both Xiamen University and WVU.
- Stress-strain curves created to find Young's Modulus and ultimate compressive strength.

Failed rammed earth sample (XMU)

Compression Testing: Rammed Earth

Chengqi earth sample before and after testing at WVU



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

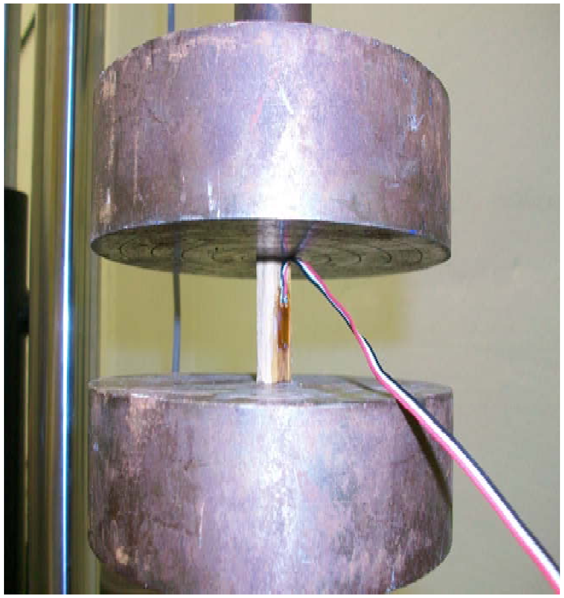
- Some reference values:
  - ✓ Soft clays E 700 - 2800 psi
  - ✓ Medium clays E 2800 - 7000 psi
  - ✓ Stiff clays E 7000 - 14000 psi
  - ✓ Rammed earth f'c 450 - 800 psi (Earth Materials).

Wall Reinforcements in RE Wall: Wood/Bark/Bamboo

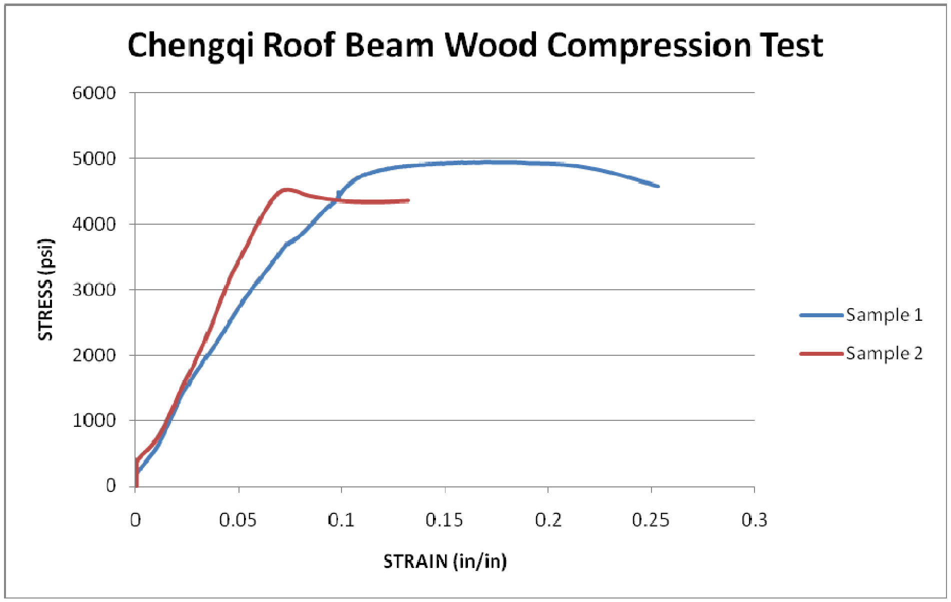
Rough rammed earth walls of Chengqi Tulou showing layer construction and wall ribs

Pultruding wall ribs

Compression Testing of Wood Sample



Chengqi Tulou wall rib sample being tested under compression at WVU



Chengqi roof beam wood sample stress/strain curve

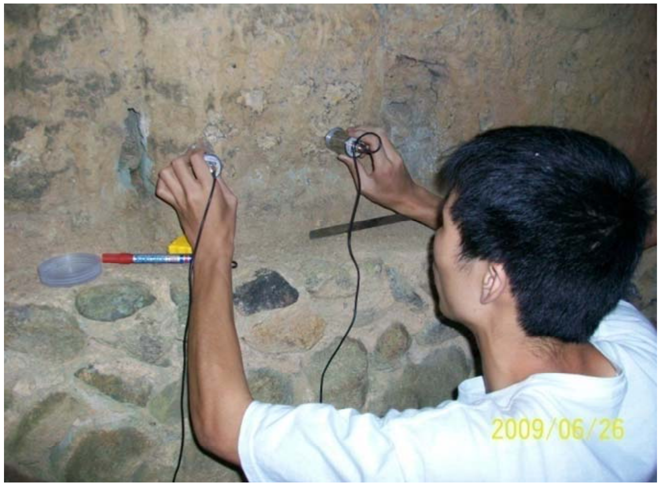
Mechanical Properties of Wood/Bamboo Samples

			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

Reference values

- ✓ Bamboo E 2.76 msi
- ✓ Wood E 1 msi

Nondestructive Testing on RE Walls: Ultrasonic



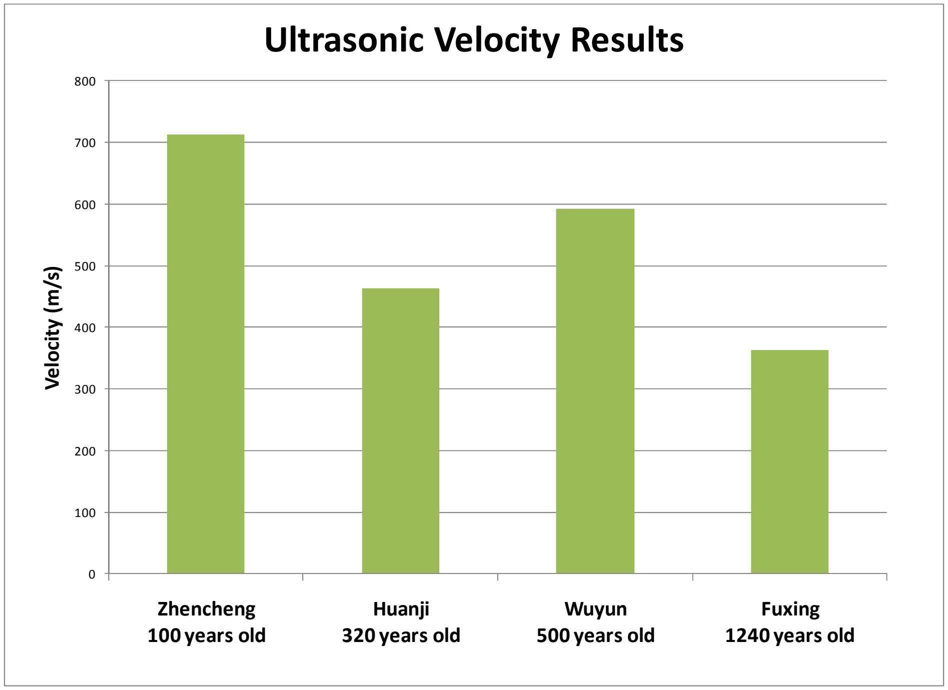
- To understand the conditions of the rammed earth walls of Hakka Tulou, without damaging the historic structures.

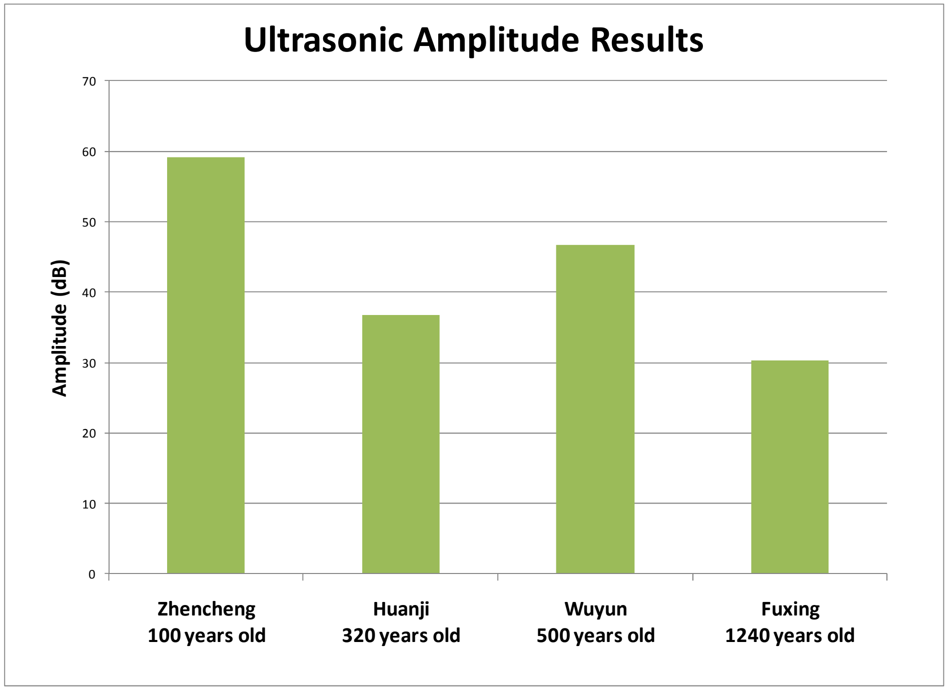
- Ultrasonic testing may reveal info about the strength of RE walls:
  - A combination of velocity and amplitude measurements provides more useful info by increasing the sensitivity of the ultrasonic technique to defects.
  - One can compare the velocity of a wave to the amplitude to see if there are inconsistencies, if inconsistencies exist then there is a possibility that a defect may be present.

Rebound Hammer Testing

- Rebound hammer test is typically used for measuring hardness of concrete samples; measures the hardness by striking a mass on a surface and measuring rebound value (Halabe et al. 1995)

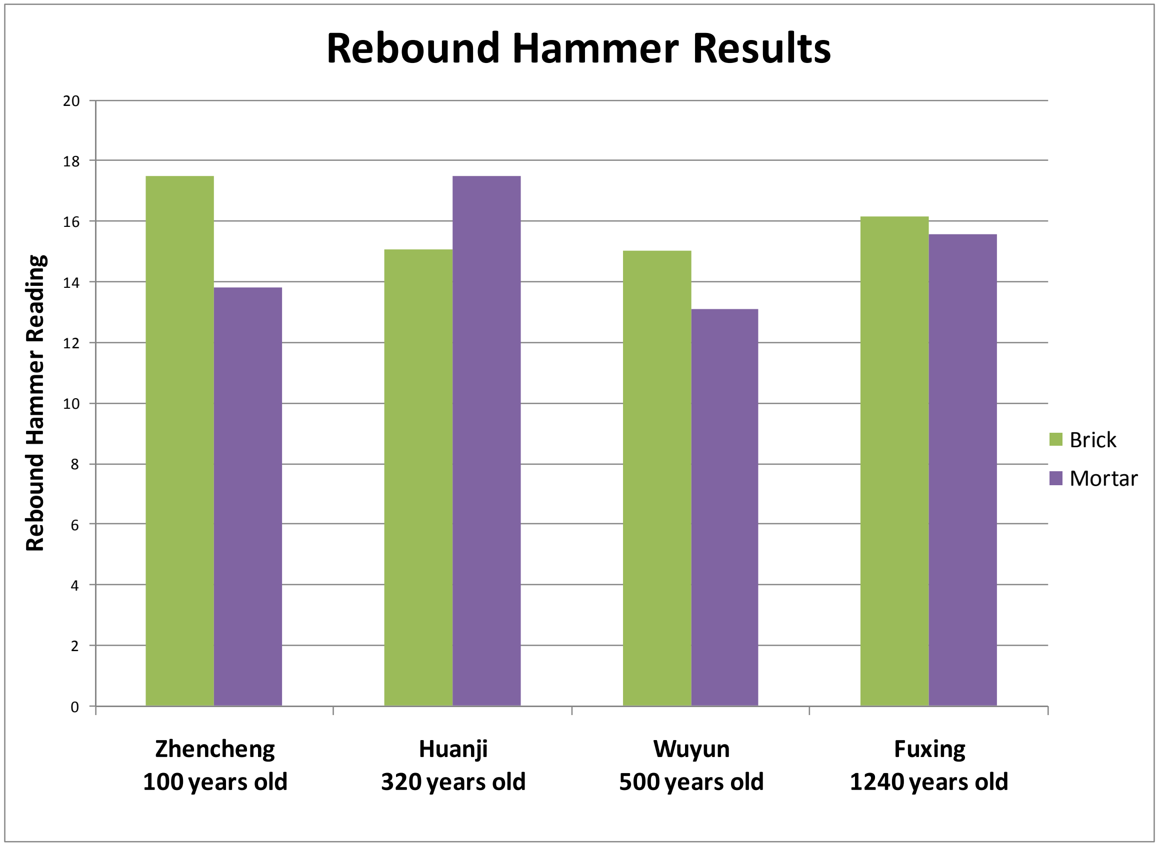
Ultrasonic Results





Note: Fuxing Tulou data obtained on wet walls due to rain

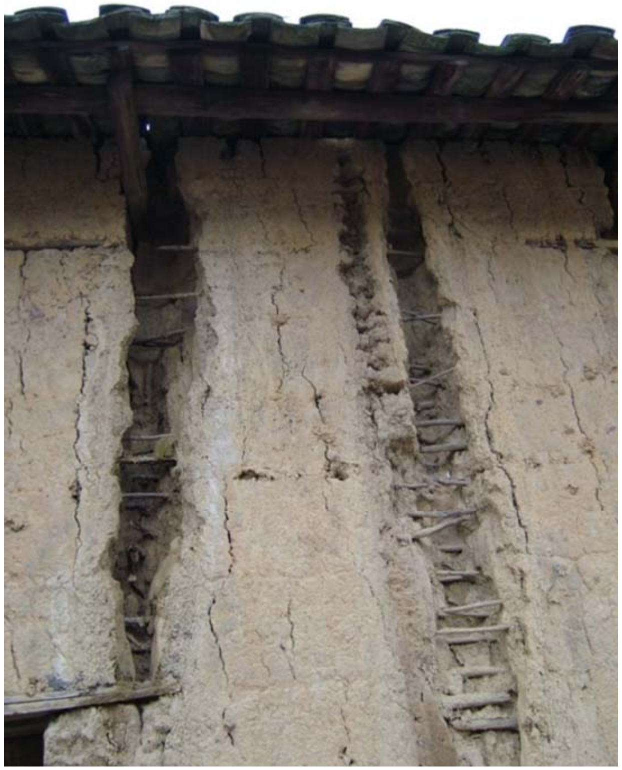
Rebound Hammer Results



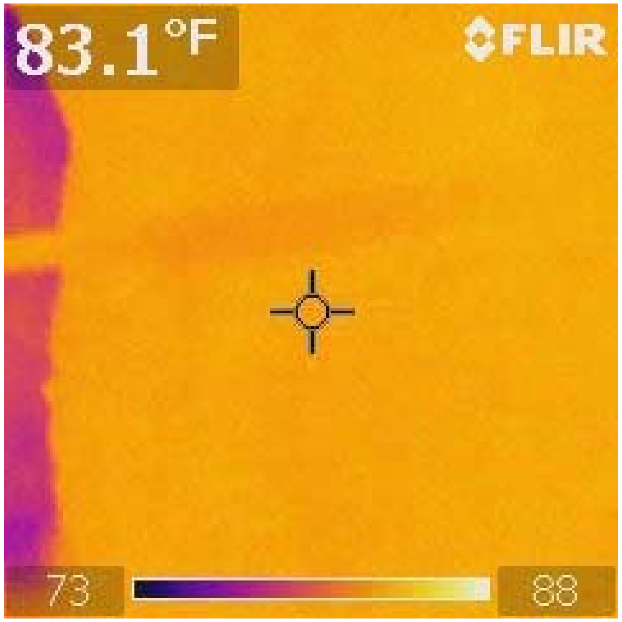
Note: Fuxing Tulou data obtained on wet walls due to rain

Infrared Thermography

Portable Handheld IRT camera used



Eroded RE wall exposing wall ribs

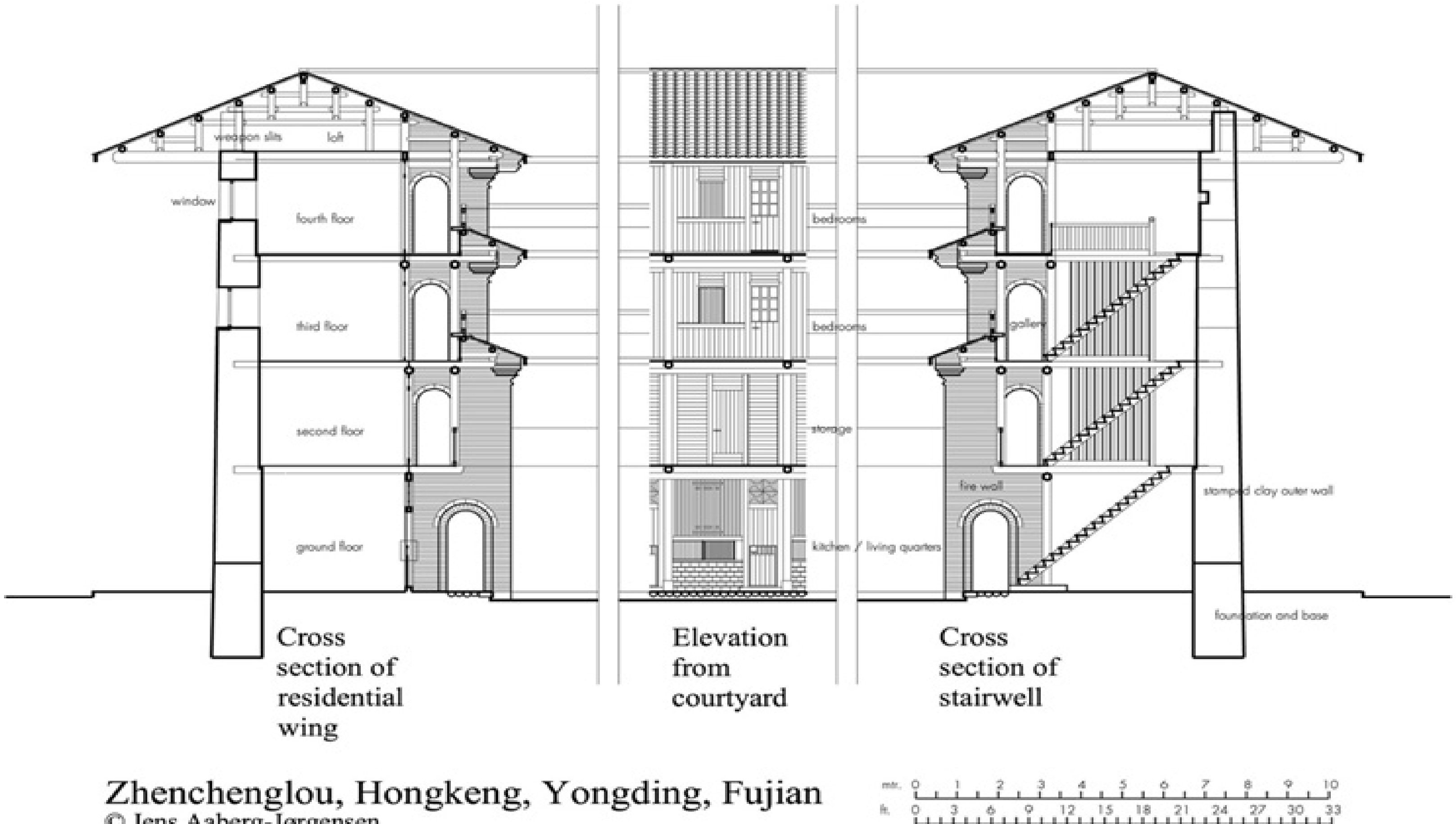


IRT detecting shallow wall rib

NDT Results

- NDE techniques such as ultrasonic and rebound hammer were proved effective to quantitatively compare the strength of rammed earth walls.
- Infrared thermography was found not sensitive enough to detect the presence of wall ribs.
- Rebound Hammer results of Fuxing Tulou further exemplify outstanding long term strength of rammed earth

Integrity of Hakka Tulou



Zhenchenglou, Hongkeng, Yongding, Fujian
© Jens Aaberg-Jørgensen

Load Testing on Roof Truss System

- Internal wooden system is important load bearing component of Tulou.
- Loads distribute from wooden roof truss down to rammed earth walls and wooden columns.
- Two point load test up to 550 lbs in order to collect the strain data to reveal structural integrity of the system.
- Both roof and floor tests performed at Chengqi Tulou.

Structural Modeling of Roof Load Test

- Structural modeling allows to:
  - ✓ Better understand the response of the structure
  - ✓ Estimate the material properties of structure by 'back-calculating'
  - ✓ Monitor how structurally sound system may be

- RISA was used to conduct the analyses in this study, which is a linear elastic modeling program.

- <u>Step 1</u>: Create model using actual dimensions

- <u>Step 2</u>: Apply load in model and compare strain gage results with model results

- <u>Step 3:</u> Adjust model modulus values to match actual results

Modeling Assumptions

- A common difficulty in modeling is to portray support conditions of a structure accurately in a model.
- Theoretically: Fixed=No rotation/No translation
  Pinned=Allows rotation/No translation
- In reality conditions actually fall in between the two (partially fixed/partially pinned).
- Reasonable assumptions must be made to most accurately simulate actual conditions.
  - ✓ Pinned Connection used for Wall-Roof Truss tie: the beam is not connected directly to the wall, it is laying in a groove made in the rammed earth wall, the frictional resistance as well as the mass of the structure will prevent it from translating and acting like a roller.
  - ✓ Wooden Columns assumed fixed as they directly tie into the foundation.
  - ✓ Connections between members assumed fixed as frictional resistance and the connection system of the members prevents the freedom to rotate in a full manner.

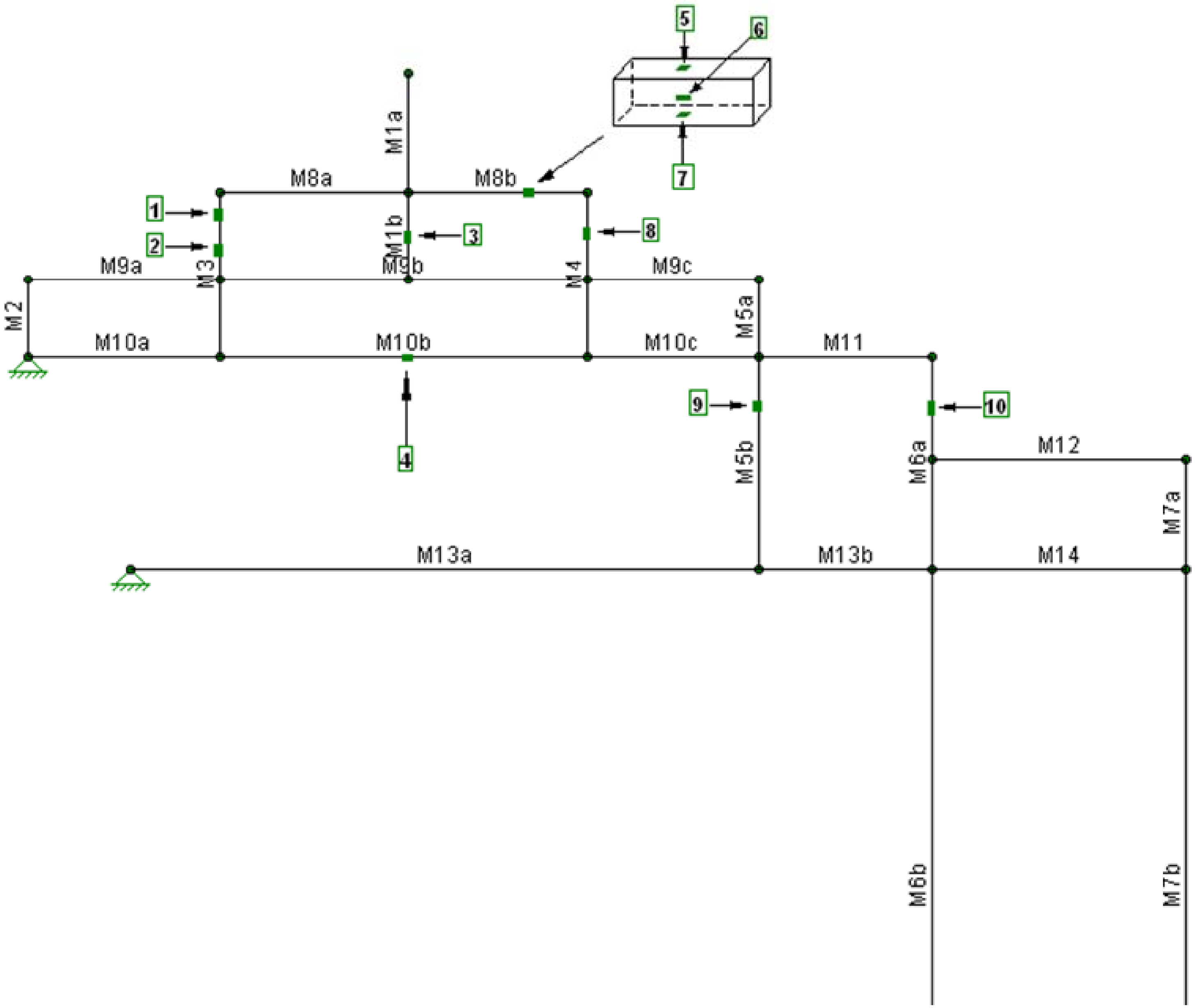
Modeling Assumptions (cont.)

- Due to difficulty in predicting how a circular column will deflect (and thus predicting strain gage location), size of the columns (dia 7”-8.5”) and relatively small load applied, axial effects were only considered for column members
  - $\sigma = E\epsilon$

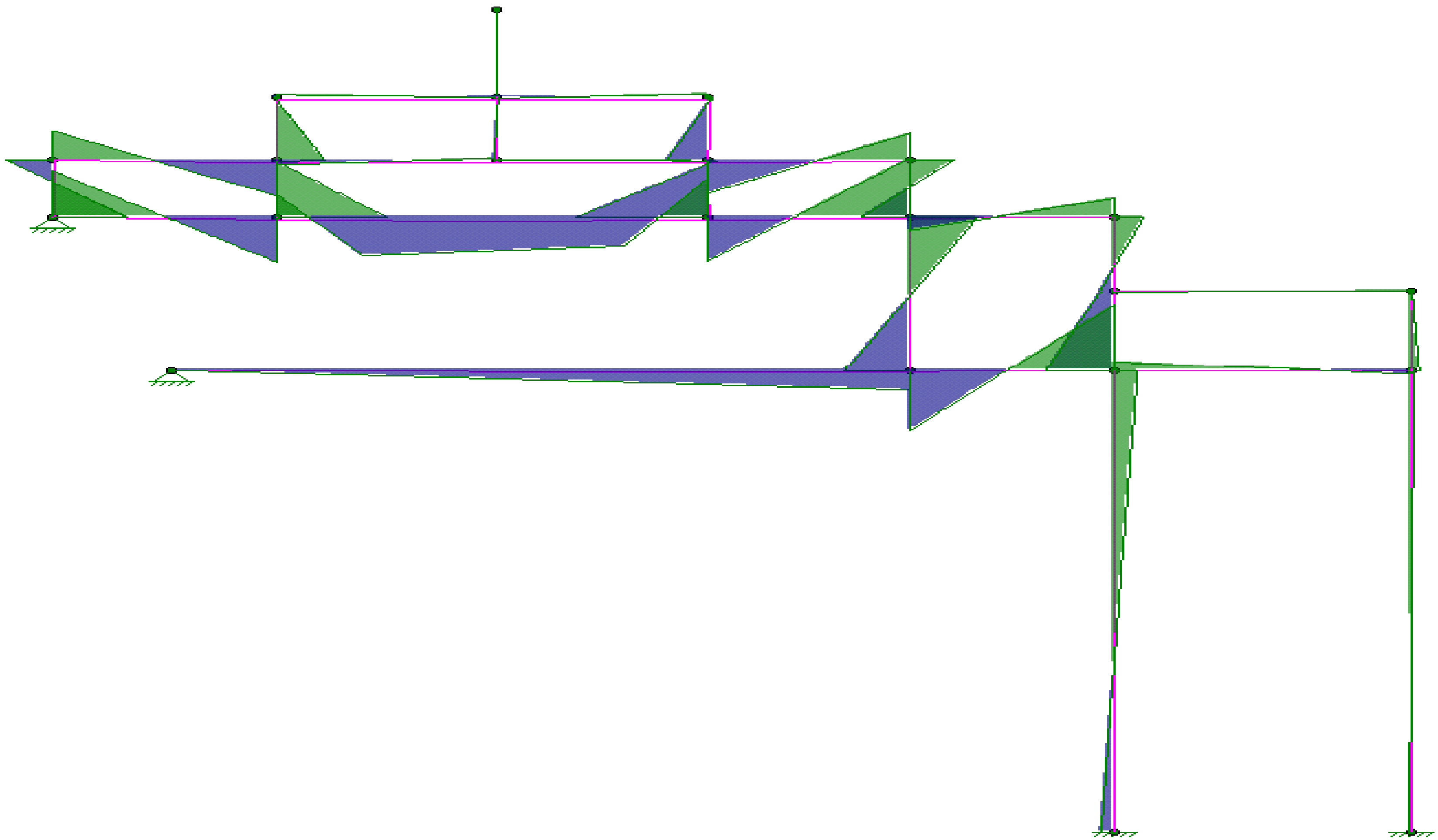
- For beams, strain gages located on bottom thus bending effects also could be considered.
  - $\sigma = \frac{My}{I} + \frac{P}{A}$

- Most accurate modeling results will be from the members closest to the loading as errors from assumptions propagate farther from loading.

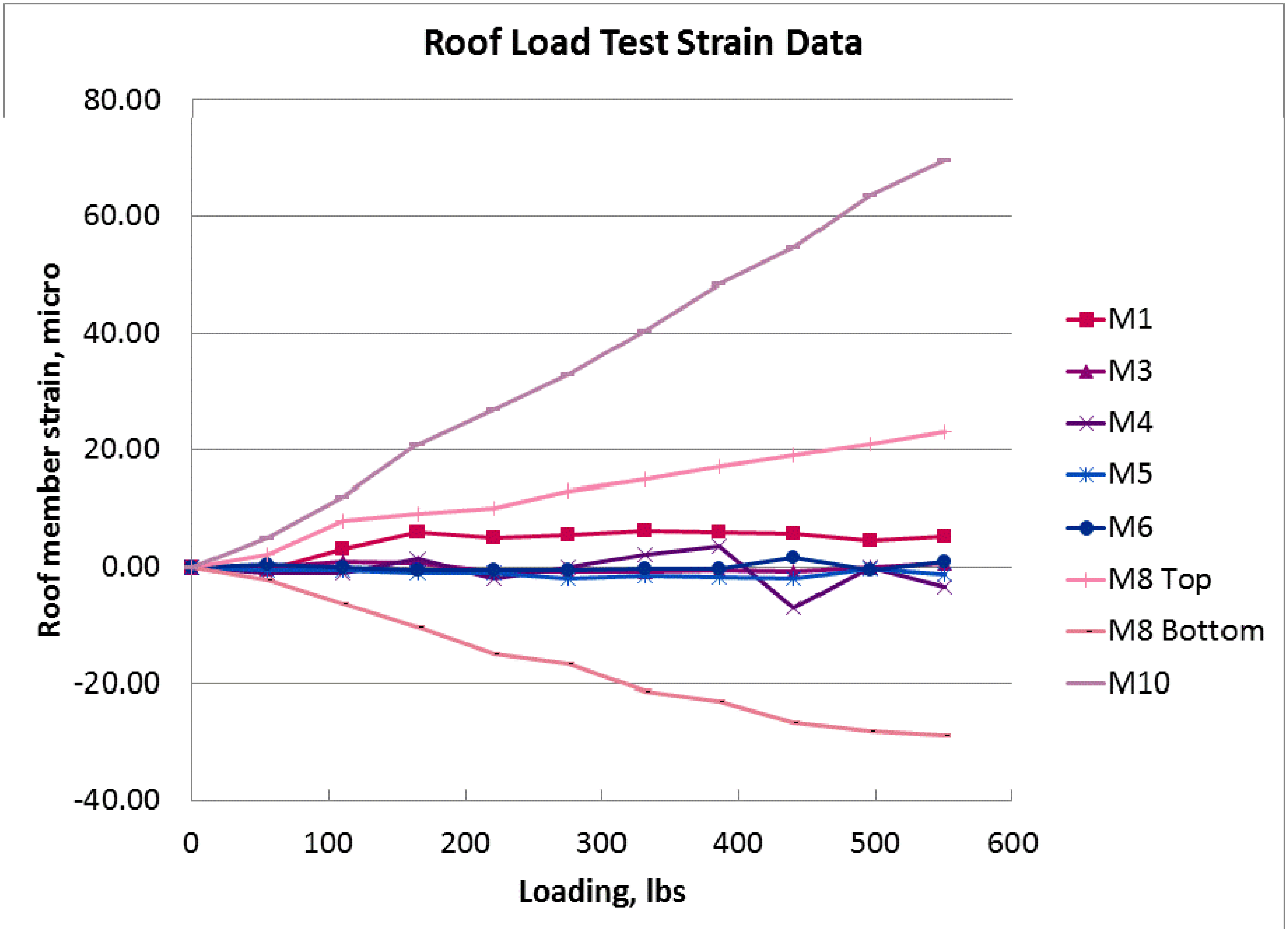
Roof Truss Member Definition and Strain Gage Locations



Moment Magnitude Distribution from Roof Truss Modeling



Roof Load Test Strain Data and Model Predictions

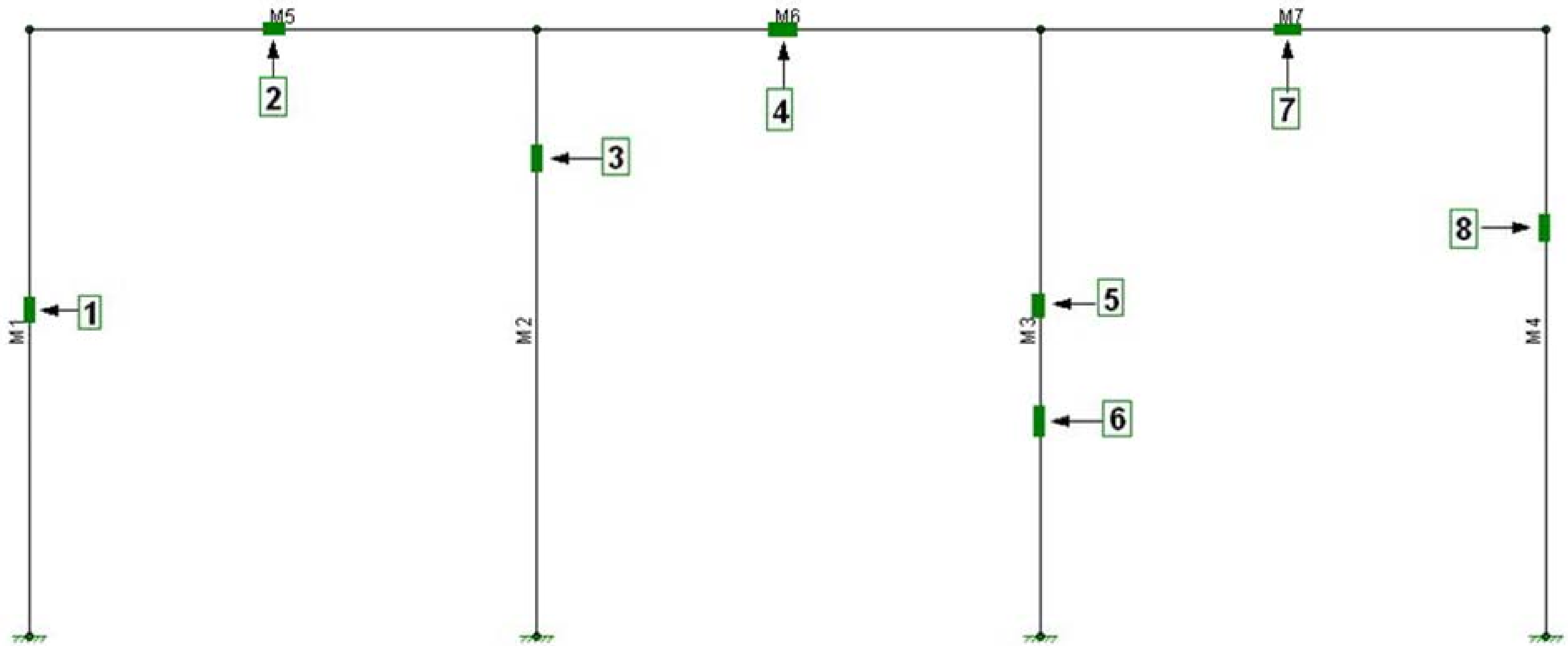


Roof System Load Test Strain Data and Model Predictions

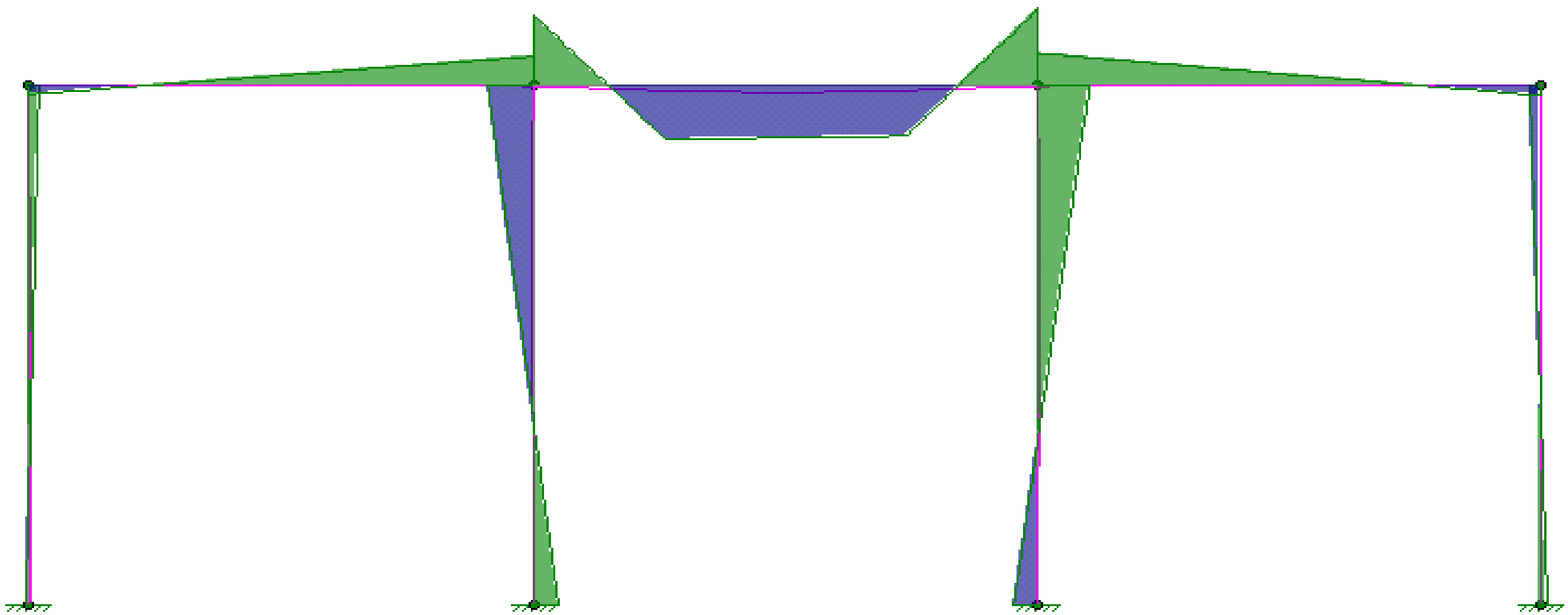
	Member	M1	M3	M4	M5	M6	M8 Top	M8 Bottom	M10
	Gauge #:	**3**	**1**	**8**	**9**	**10**	**5**	**7**	**4**
	Load, lbs	**με**	**με**	**με**	**με**	**με**	**με**	**με**	**με**
Field Test Data	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	55	-0.50	0.00	-1.00	-0.50	0.40	2.00	-2.33	5.00
	110	3.00	0.83	5.00	-0.60	0.00	8.00	-6.25	12.00
	165	6.00	0.75	6.00	-1.00	-0.60	9.00	-10.33	21.00
	220	5.00	-0.67	14.00	-1.00	-0.50	10.00	-15.00	27.00
	275	5.50	-0.75	17.00	-2.00	-0.60	13.00	-16.67	33.00
	330	6.33	-0.67	22.00	-1.50	-0.33	15.00	-21.25	40.33
	385	6.00	-0.50	24.00	-1.67	-0.20	17.00	-23.00	48.50
	440	5.67	-0.67	24.00	-2.00	1.60	19.00	-26.67	54.67
	495	4.50	0.00	22.00	-0.33	-0.50	21.00	-28.00	63.50
	550	5.33	0.67	19.00	-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

Load Testing of Floor System

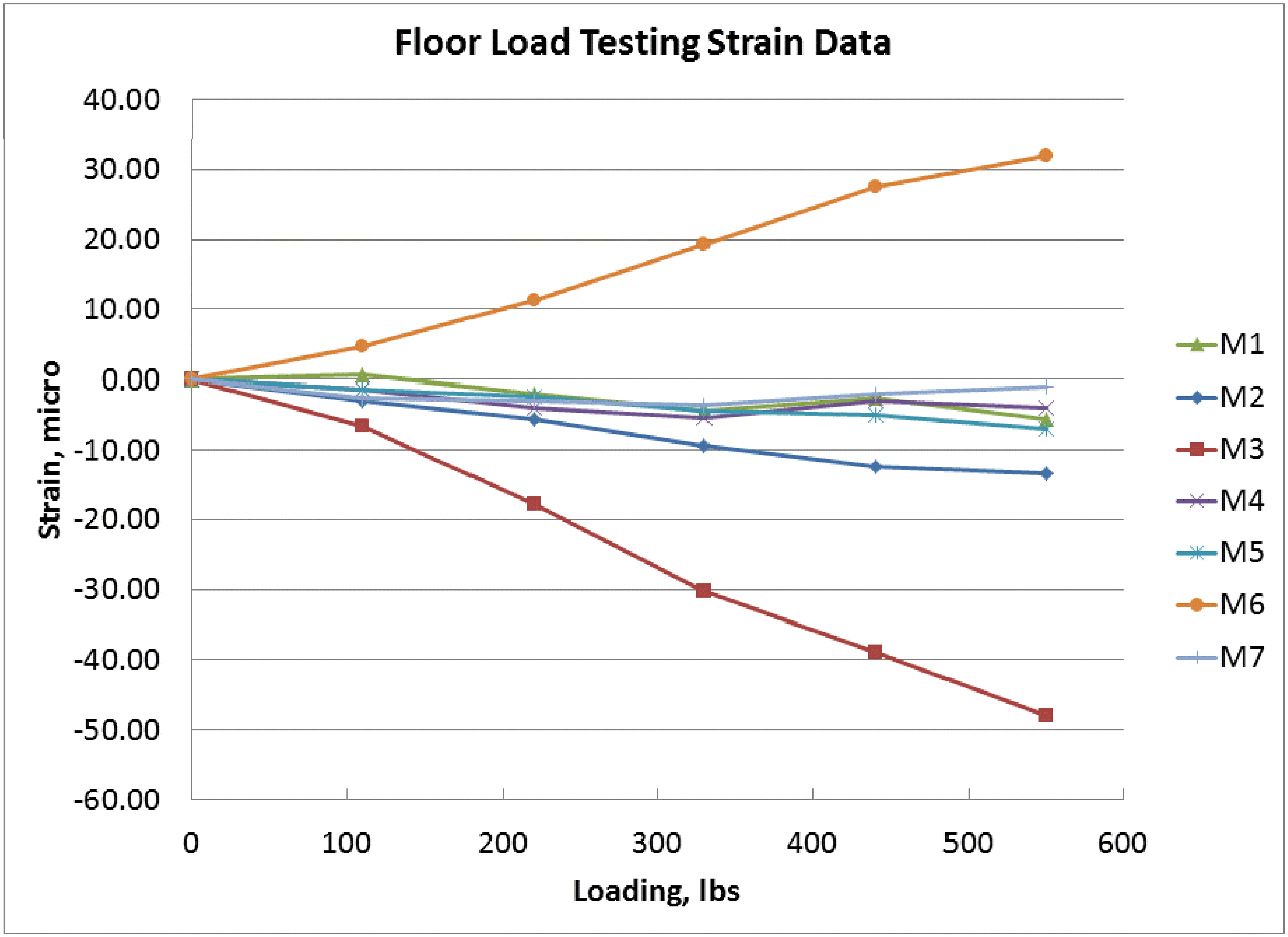
Floor Member Definition and Strain Gage Locations



Floor System Modeling



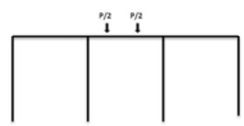
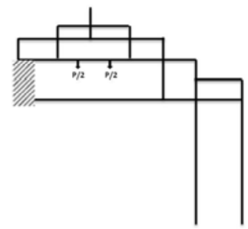
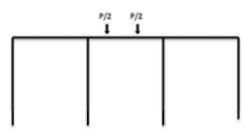
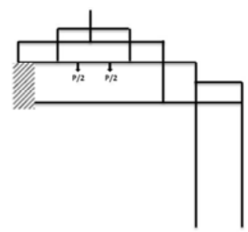
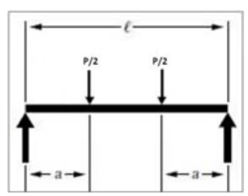
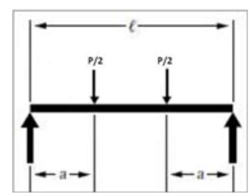
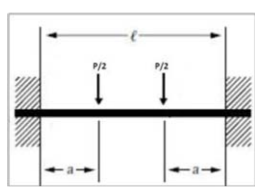
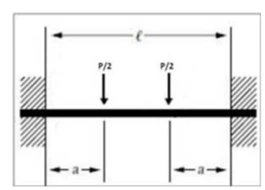
Floor System Member Strain Data



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

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)**

Findings from Load Testing on Roof and Floor System

- Both systems structurally sound (no significant strain)
  √ Roof Truss: 70 microstrain @ 550 lbs >>> E=0.85 msi matches
  √ Floor System: 32 microstrain @ 550 lbs >>> E=1.85 msi matches

- Both systems are made of China-fir (2 msi) that offers such high strength and high decay resistance as well.

- As compared to 1) a simply supported beam and 2) a beam fixed at both ends,
  √ Roof Truss: 311 microstrain @ 550 lbs 101 microstrain
  √ Floor System: 68 microstrain @ 550 lbs 17 microstrain

- 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. The jointed neighboring members have a high load-sharing effect in a manner similar to a fixed beam.

- The roof truss system being tested is providing extra stiffness, resulting in a microstrain of 70 only, meaning 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.

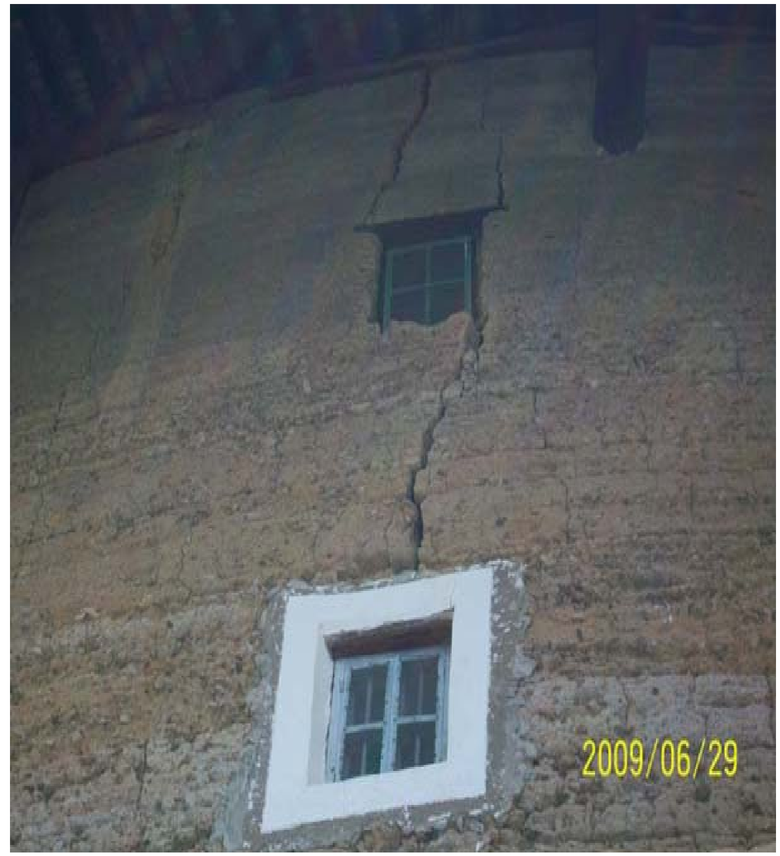
FE Modeling of Earthquake Resistance

- To model the creation of the existing crack at Huanji Tulou and attempt to validate its self healing claim.

- To model the response of Huanji Tulou under a strong quake load and explain its strong resistance to earthquakes.

Description of the Crack of Huanji Tulou

- It is believed: In 1918 an earthquake measuring 7.0 (Richter) struck the Huanji Tulou (built in 1693). This earthquake created a crack in the rammed earth wall that supposedly was 20 cm in width and 3 meters in length.
- This study: Crack now measured at 5 cm in width at its narrowest, crack across the entire wall thickness. Huanji RE wall has NO internal reinforcement.

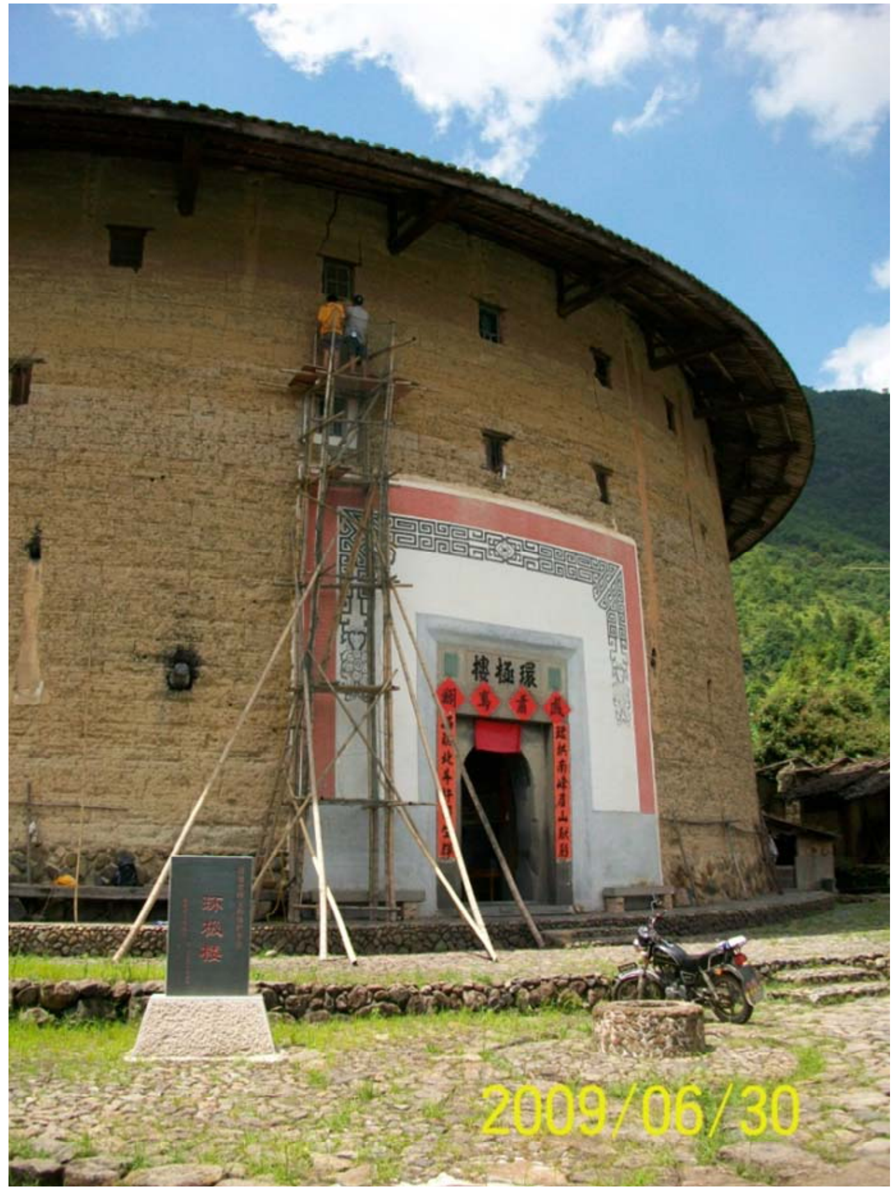


Huanji Tulou Crack-after-earthquake

Location of Huanji Tulou Wall Crack

Access Platform was built during field study in the Summer of 2009.

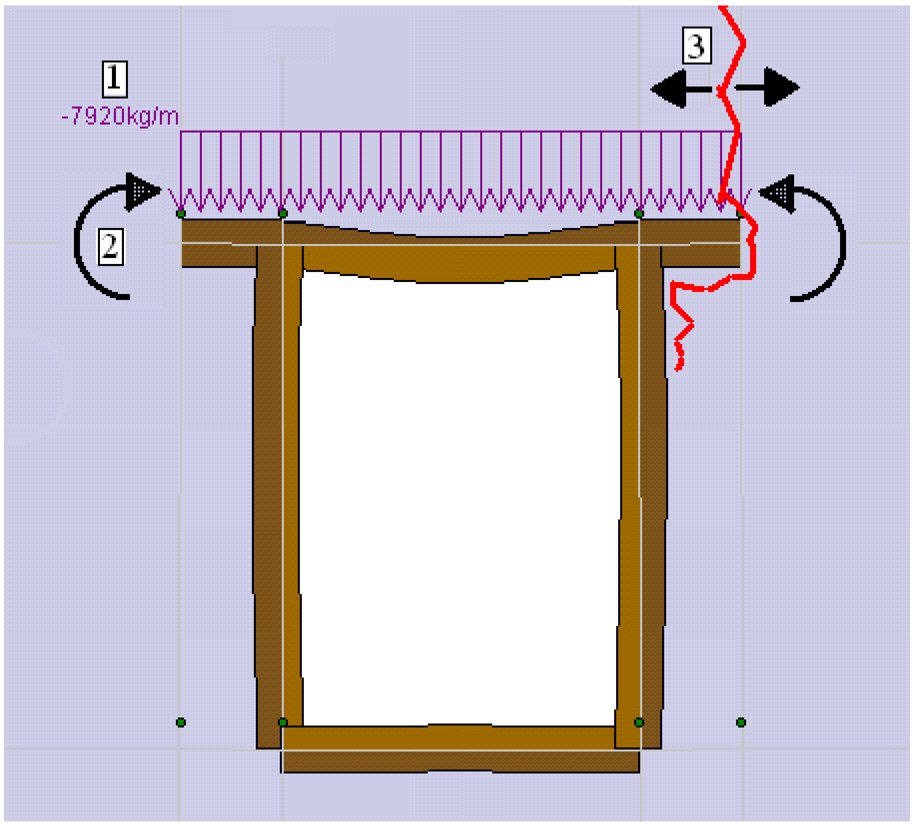
The through-the-wall thickness crack of Huanji Tulou



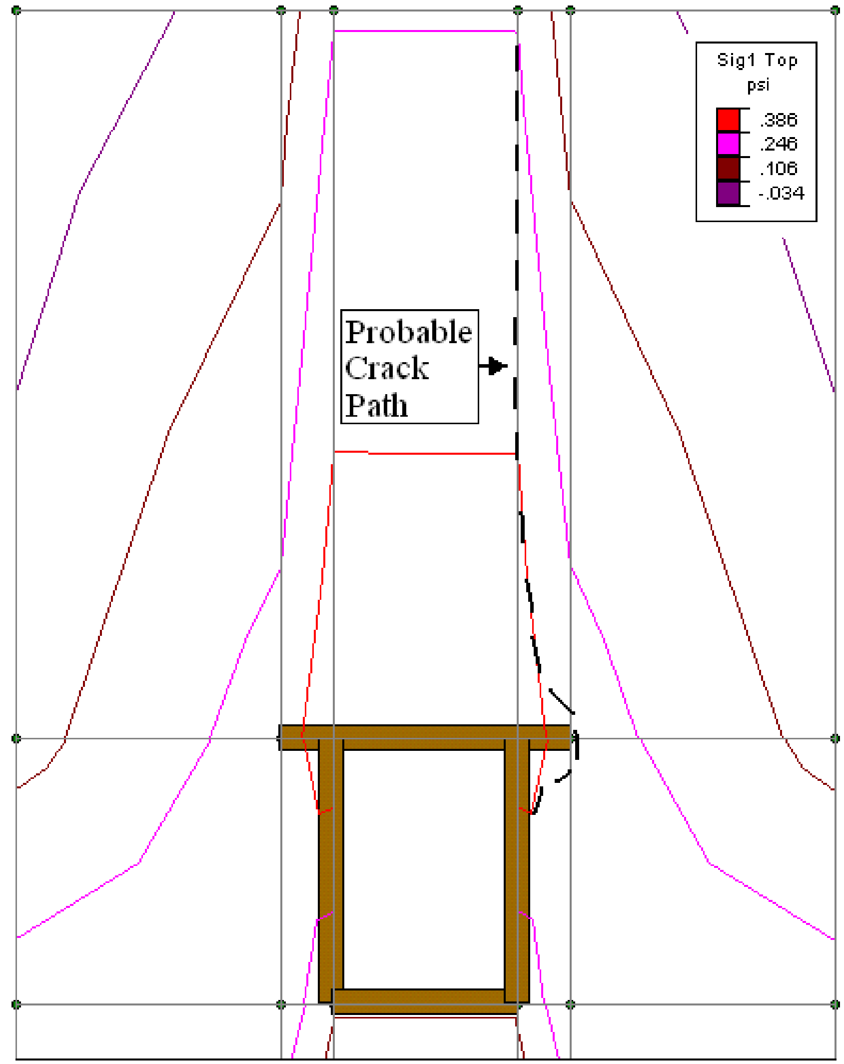
How Did Crack Develop?

- Knowing that rammed earth has a density of 1600 kg/m^3 as well as lintel/wall dimensions, one can re-create cracking scenario in FE modeling.
  - √ Wall height above lintel=2.75m
  - √ Wall thickness=1.8m
  - √ 2.75m*1.8m*1600kg/m^3=7920kg/m

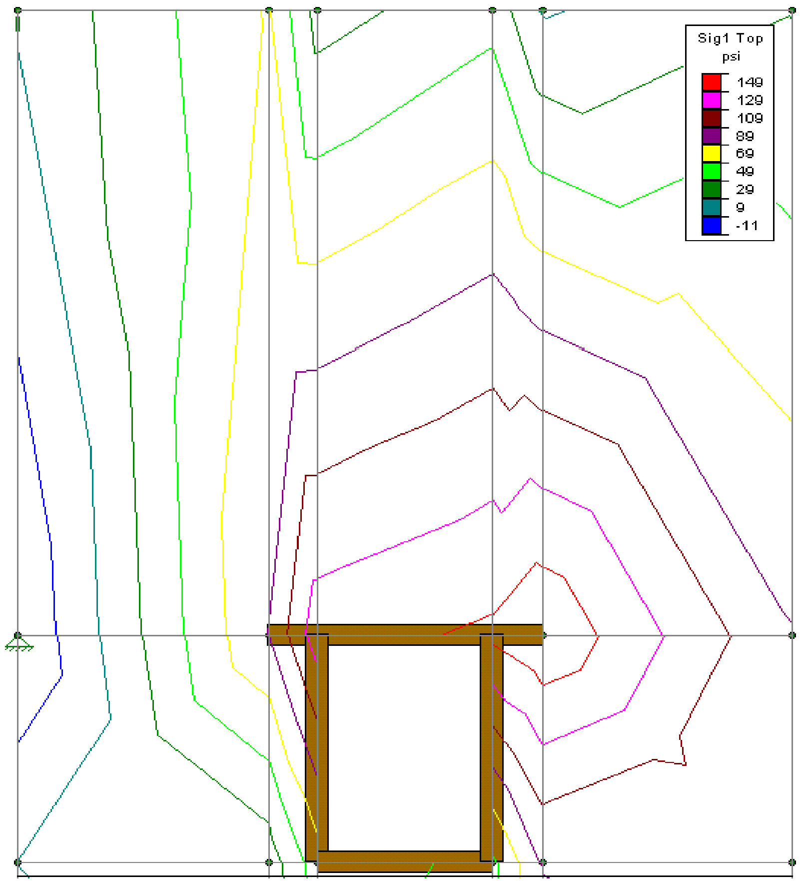
- Step 1: Dead Load acting on lintel initially causes bending and subsequent stresses.
- Step 2: Bending moment upwards at lintel ends.
- Step 3: Rammed Earth experiences compression in vertical direction(σ_1) and due to poisson's effect experiences tension in horizontal direction (σ_2).

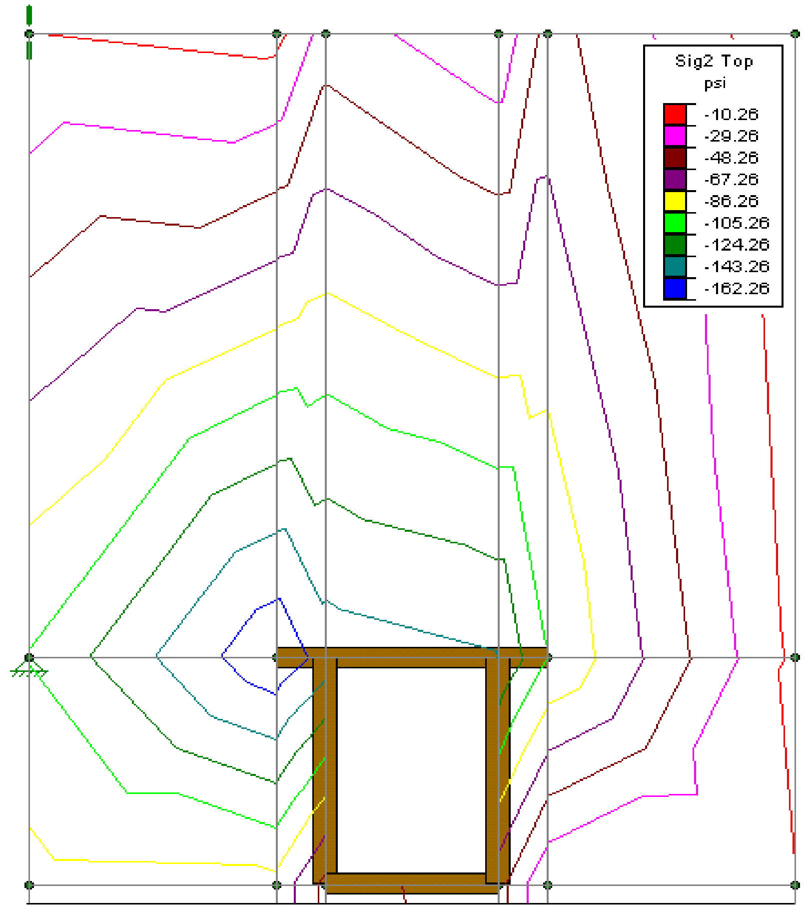


The Cracking and Cavity at Lintel End



Stresses due to Horizontal Load Induced by Earthquake





- In order to re-create possible cracking of rammed earth wall:
  - 225 kip (1000 KN) load applied 4 m below lintel (coincides with MCE by ASCE 7-05).
  - Pinned support added (left of lintel) to force structure into higher mode of deflection.
  - Lowest ult. compressive stress tested: 126 psi (Zhencheng Tulou).
  - Important to note that ult. tensile stress is much lower in rammed earth (similar to concrete).

How crack could have been prevented

- Uncoincidentally, Huanji Tulou has no internal reinforcement.

- By using Rule of Mixtures, one can see how such reinforcement could strengthen rammed earth walls to prevent crack from occurring.
    - ✓ $E_1=E_fV_f+E_m(1-V_f)$

- Based on wall rib samples collected,
    - Avg wooden sample round ~1.5” dia
    - Avg bamboo sample 0.5”x1”
    - This is an estimate as sample sizes vary

- If one is to assume same spacing for bamboo and wood in image shown, as well as the above sample sizes, one can calculate the volume fractions of reinforcement as found in the table.

- All values used are most conservative options (i.e. the weakest wood sample and rammed earth sample among tested.

Type of Reinforcement	Volume Fraction (%)	Fiber Modulus of Elasticity (psi)	Composite Longitudinal Modulus, E_1 (psi)
None	n/a	n/a	1705.5
Wood	6.70%	34736.67	3918.6
Bamboo	1.80%	463178.1	10012

Self Healing of Crack?

Locals claim that the crack has self healed after the earth quake. We wonder what would be the possible mechanism for such self healing (if any).

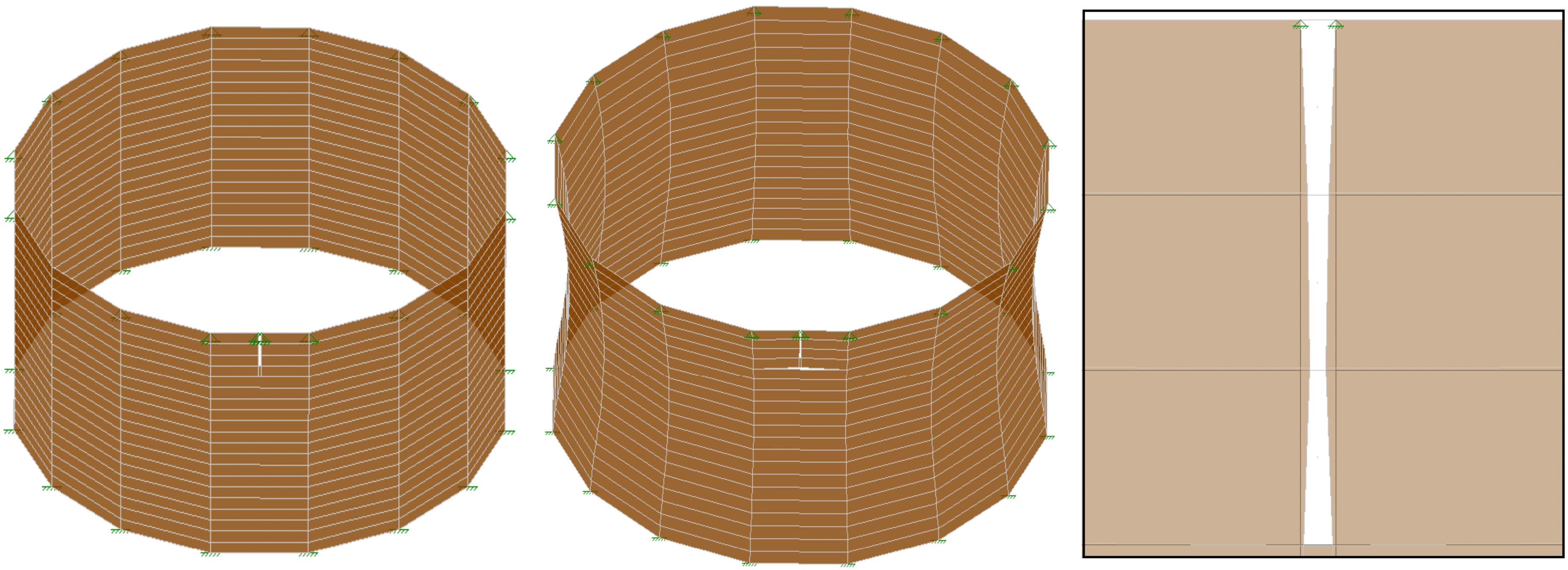
- Autogenous Healing has been proven in Concrete with the existence of lime and water, however crack sizes are always smaller than 1 mm.
  - ✓ As cracks appear in concrete systems, water infiltrates the cracks and dissolves any lime that it may come in contact with. The dissolved lime is then taken to the surface of the crack where it carbonates and begins to heal the crack (Rhydwen, 2007).
  - √ This re-cementing of concrete systems depends on several factors including age, degree of contact of the crack, curing conditions, moisture conditions, and most importantly the availability of lime or fly ash (Angelbeck, 1978).
- The crack at Huanji is 5 cm at its narrowest. The above re-cementing is not applicable. Also EDS chart shows no lime existence in Huanji rammed earth.

Self Healing of Crack? (cont'd)

- Thermal Expansion effect. The Model of Huanji Tulou created previously was used to show how crack could possibly close up due to thermal loads.

  √ Coefficient of thermal expansion for a clay brick used: 0.0000033 in/in/°F (Friedman, 2006)
  √ Model height=20 m, wall thickness=1.8 m, and outer diameter of 43.2 m
  √ 20 plates per unit used, having plate height of 1 meter and plate thickness of 1.8 meters
  √ Fixed base at foundation, pinned end condition at top to represent roof restraint that also ties into foundation through wooden columns.
  √ Crack of 20 cm in width and 3 m in height also recreated in model
  √ Applied -70° F thermal load in order for crack to close ~50%

Model Analysis of Thermal Expansion



•At the most extreme point crack closes from 20 cm to 9.2 cm due to -70° F thermal load.

•Results are reversed when temperature is increased.

Self Healing of Crack? (cont'd)

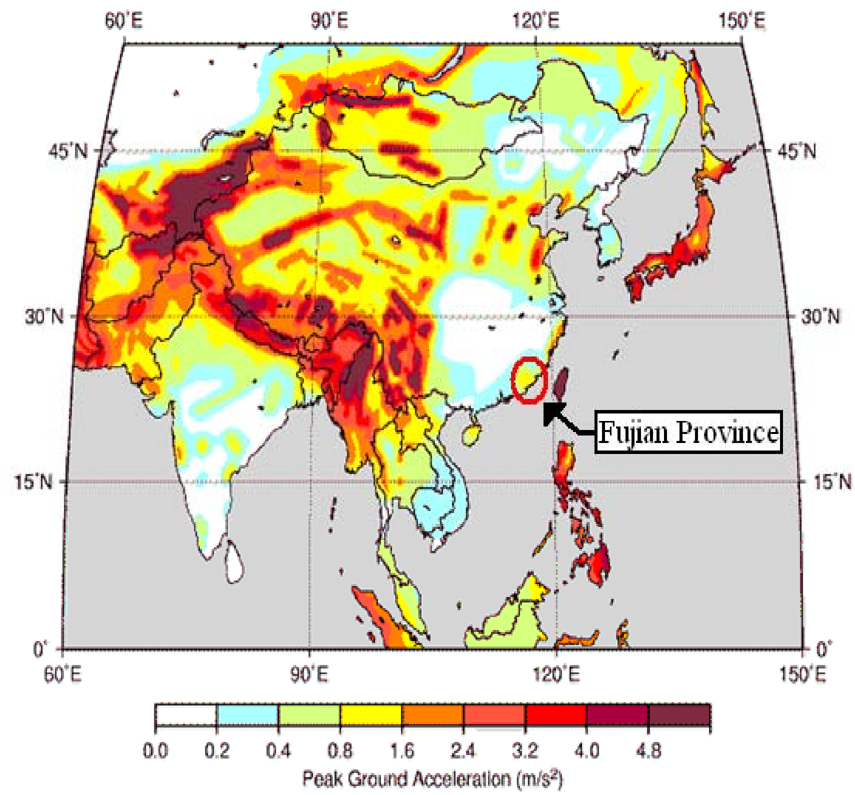
- The model shows that there is the possibility for the crack to decrease in size with decreases in temperature. However, Fujian Province has mild winters and 70 °F temperature fluxes are highly unlikely. Also, thermal expansion effect is reversal as temperature increases.

- It is argued that a thick reinforced rammed wall coupled with the internal wooden structure might contribute to a self healing effect. However, the Huanji Tulou is found without any reinforcement.

- The existence of cavity at lintel end as shown in the photo implicates that the crack has not self-healed.

Modeling Hakka Tulou under Earthquake Load

- As per reference, since the 11th century seven earthquakes of above magnitude 5 on the Richter scale have been recorded in the region.
- No structural damage reported at any of the rammed earth Tulou.
- The simplified lateral force analysis procedure provided by ASCE-7 was used to understand how the Tulou behaves during a maximum considered earthquake (MCE).



China Seismic Map (Zhang et al.)

ASCE-7 Simplified Lateral Force Analysis

- Simplified lateral force procedure typically used for frame type structures no taller than 3 stories
  - √ Method focuses on base shear rather than the dynamic response from an earthquake
  - √ The base shear from an earthquake is of primary concern for short structures as dynamic effects control for taller structures
- Due to the thickness of the wall 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 herein are thus the effects of base shear being distributed throughout the four floors of the structure (Huanji Tulou)
- 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
- Conservative parameters were used throughout modeling (E=1706 psi for rammed earth)
- Model displays applied stresses and modulus of elasticity only impacts deflections of the structure. Varying material strength will change when material would enter inelastic zone as well as when material would ultimately fail. With lower modulus of elasticity the building would deflect more and enter the inelastic zone much sooner than a stronger material

ASCE-7 Simplified Lateral Force Analysis (cont'd)

$$V = \frac{F\,S_{DS}}{R} W \qquad S_{DS} = \frac{2}{3} F_a S_s$$

V =Base Shear for maximum considered earthquake
W =Effective Seismic weight of the structure
R =Response modification coefficient

- ✓ Taken as 1.5 for a bearing wall system made of ordinary plain masonry walls

F =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}=Design spectral response acceleration at short periods, 5% damped
F_a =Short period site coefficient at 0.2 seconds

- ✓ 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 =Mapped spectral response acceleration, 5% damped, at a period of 1 second

From GSHAP map, peak ground acceleration (PGA) for the Fujian Province varies from 0.8-1.6 m/s^2

Convert PGA to S_s by multiplying by a factor of 2.5

ASCE-7 Simplified Lateral Force Analysis (cont'd)

- To be conservative, a PGA of 1.6 m/s^2 was multiplied by 2.5 to get 'S_s' =4
  - ✓ ASCE-7 ,'S_s' needs not be taken higher than a value of 1.5, thus coefficient, 'F_a'=1.0
  - ✓ Plugging in the 'S_s' and 'F_a' values of 1.5 and 1.0 into base shear equation, 'S_{DS}' = 1.0
- One can then plug this 'S_{DS}' value back into base shear equation to get this simplified equation:

$$V = .8W$$

- Knowing density, height of 20 meters, and area of the Huanji Tulou (1.8 m thick wall, outer diameter 43.2 m) results in total weight of the structure of $7.49*10^6$ kg ($16.5*10^6$ lbs) which results in a total base shear of $5.99*10^6$ N ($13.2*10^6$ lbs)
- Vertical distribution of the force that must be applied to each floor of the structure,

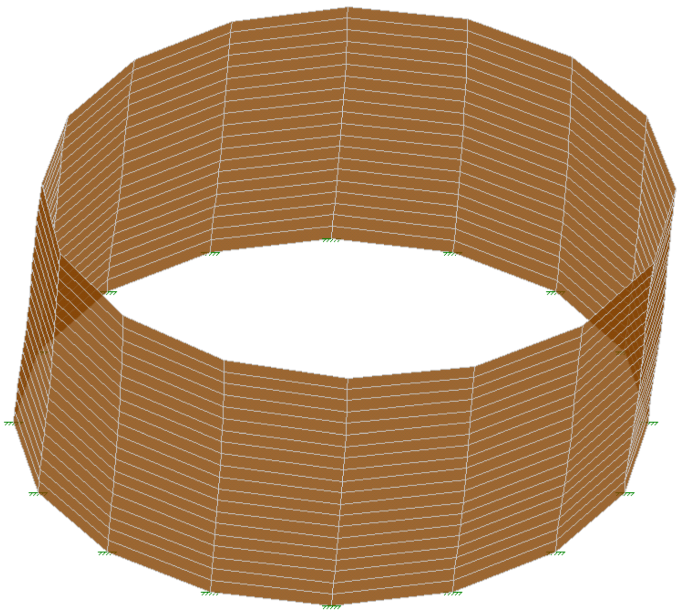
$$F_x = \frac{w_x}{W} V$$

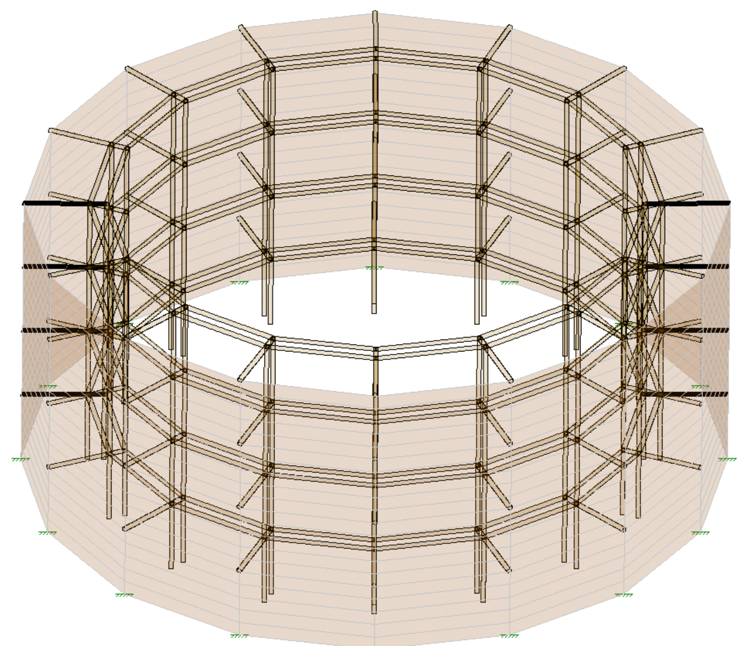
- W_x =the portion of the effective seismic weight of the structure
- 4 evenly spaced floors →Force per floor =1/4 total base shear =$3.3*10^6$ lbs
- 16 nodes per floor→ per node lateral load for each floor =206,452 lbs
- Loads applied in simultaneous direction on all 16 nodes/each floor representing MCE

Structural Responses of Tulou Under Earthquake Loads

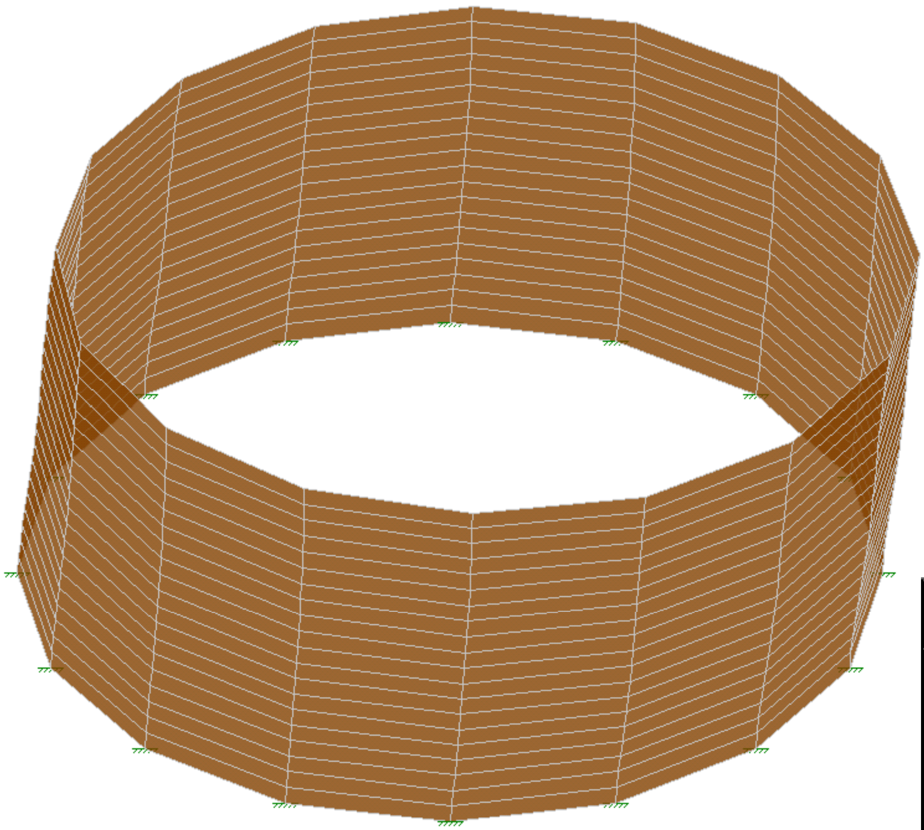
FE modeling was conducted under three variations:

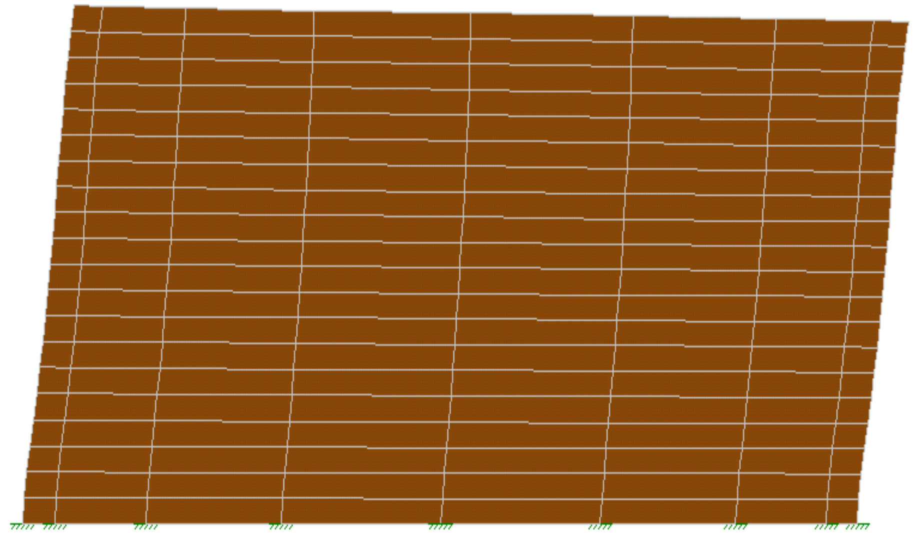
1) Rammed earth wall construction without inner wooden structures
2) Reinforced rammed earth wall without wooden structures
3) Rammed earth wall with wooden structures.





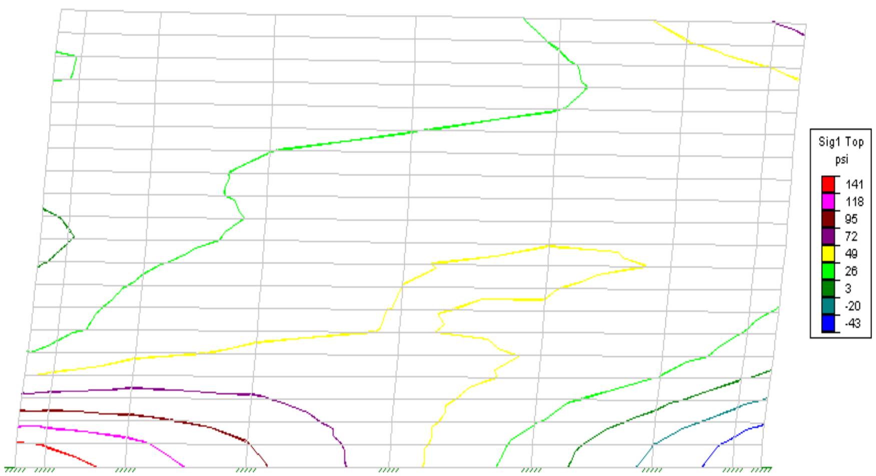
Effect of Rammed Earth Modulus on the Maximal Deflection

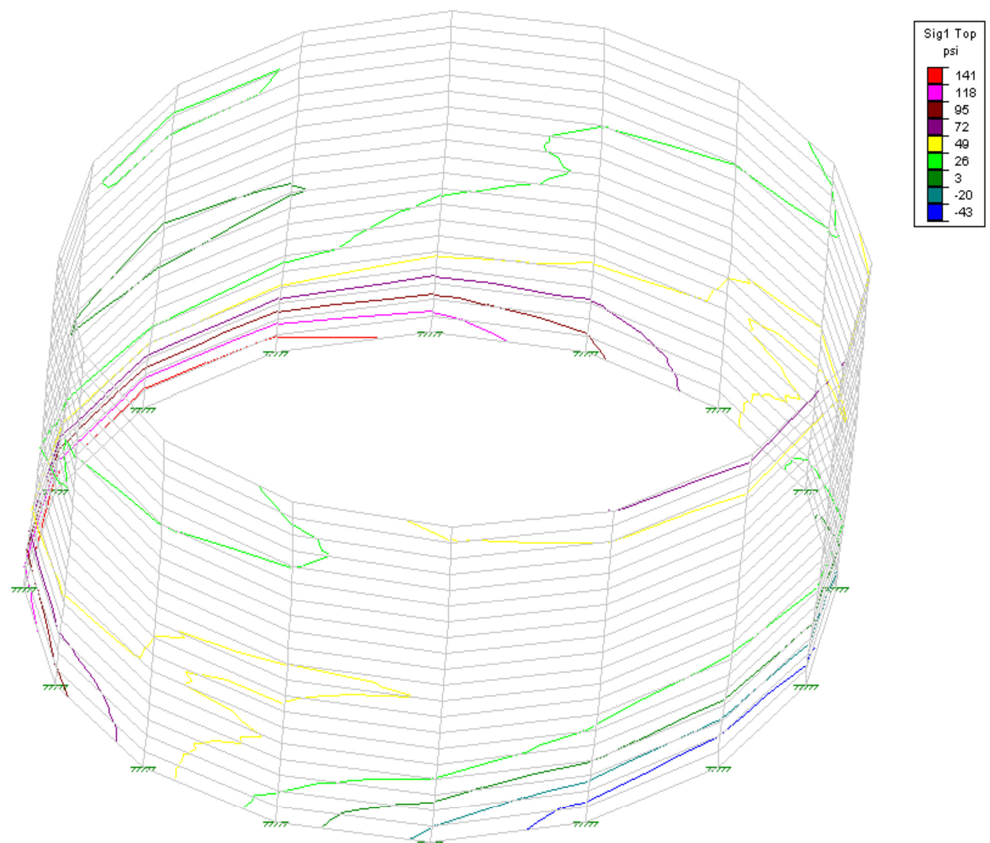




Material	E (psi)	Max Δ (m)
Weakest R. Earth	1,706	2.5
R.Earth+wood	3,919	1
R.Earth+bamboo	10,012	0.4
Strongest R.Earth	8,147	0.5

2D and 3D Stress Distribution of Tulou Under Earthquake Loads

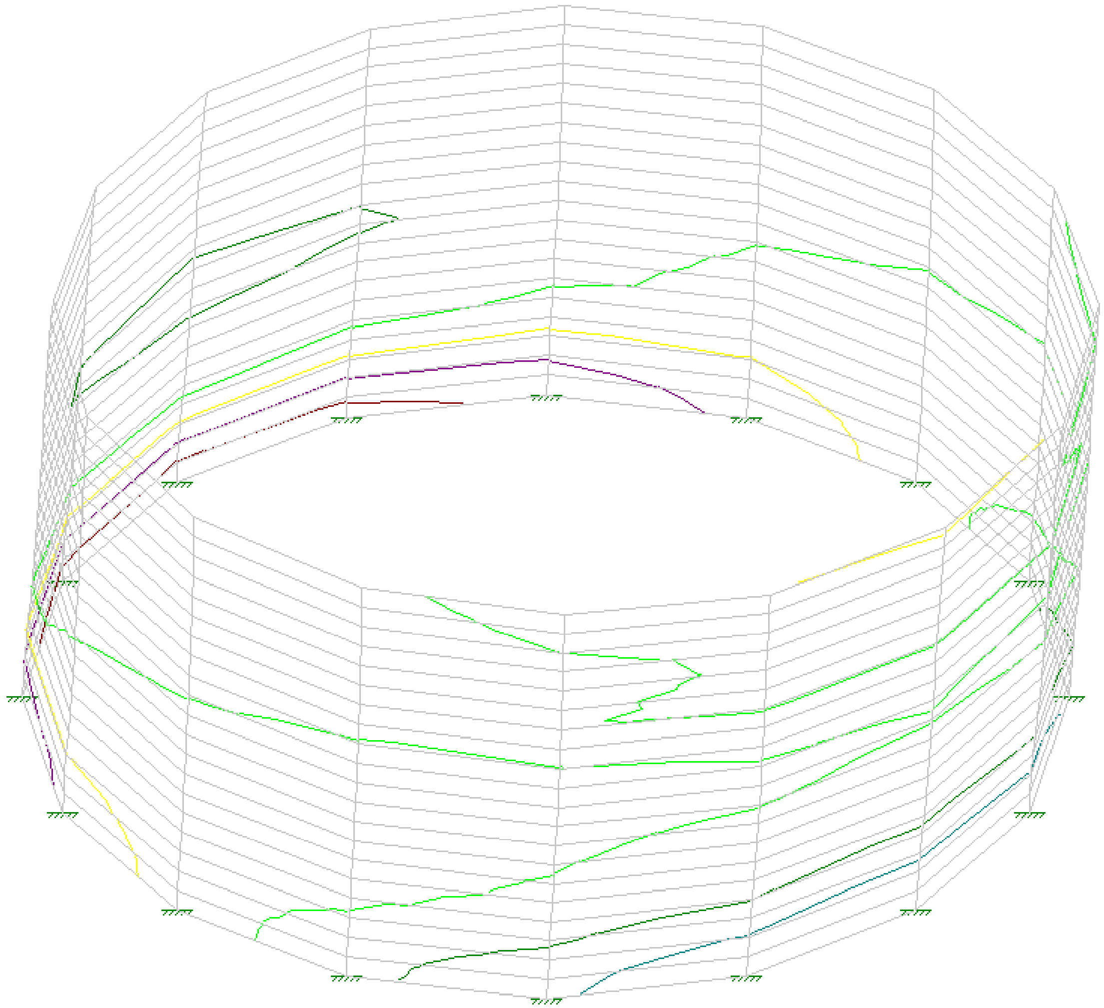




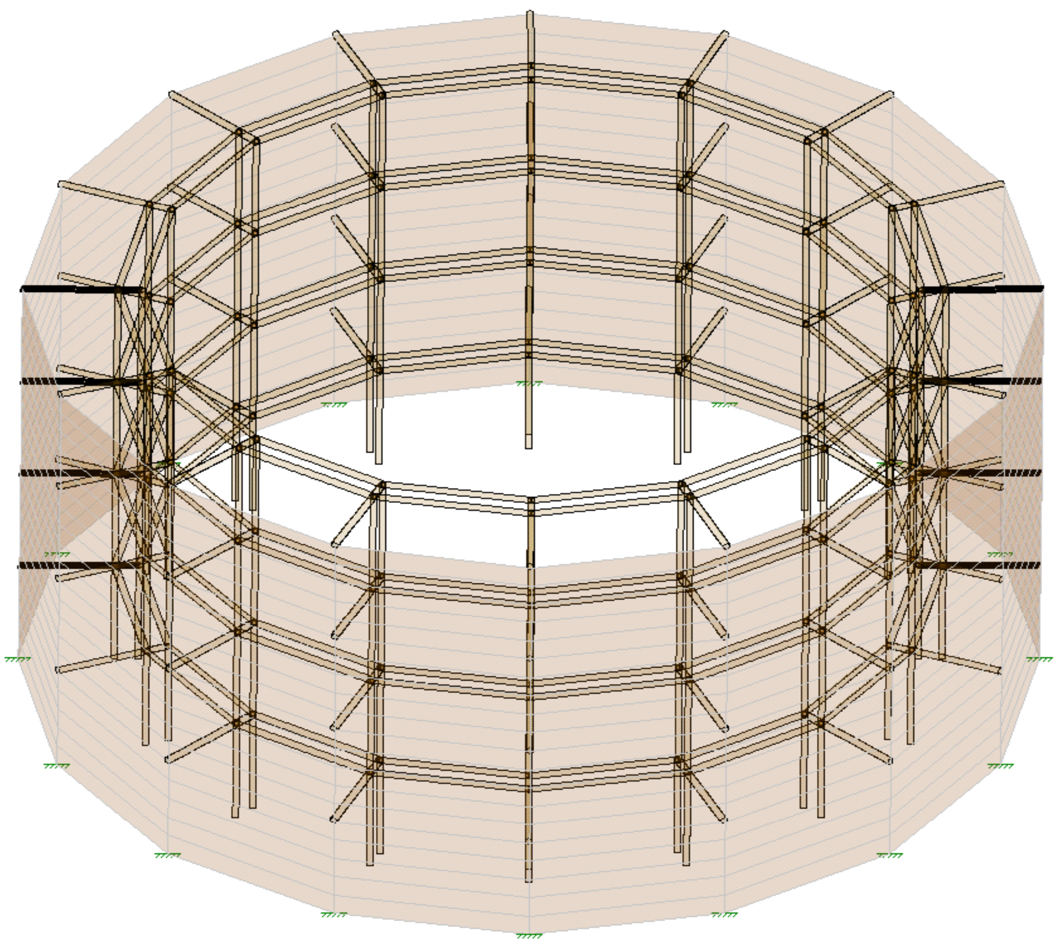
Most conservative scenario:

- ✓ Weakest rammed earth
- ✓ Without wall rib reinforcement
- ✓ Without inner wooden structure

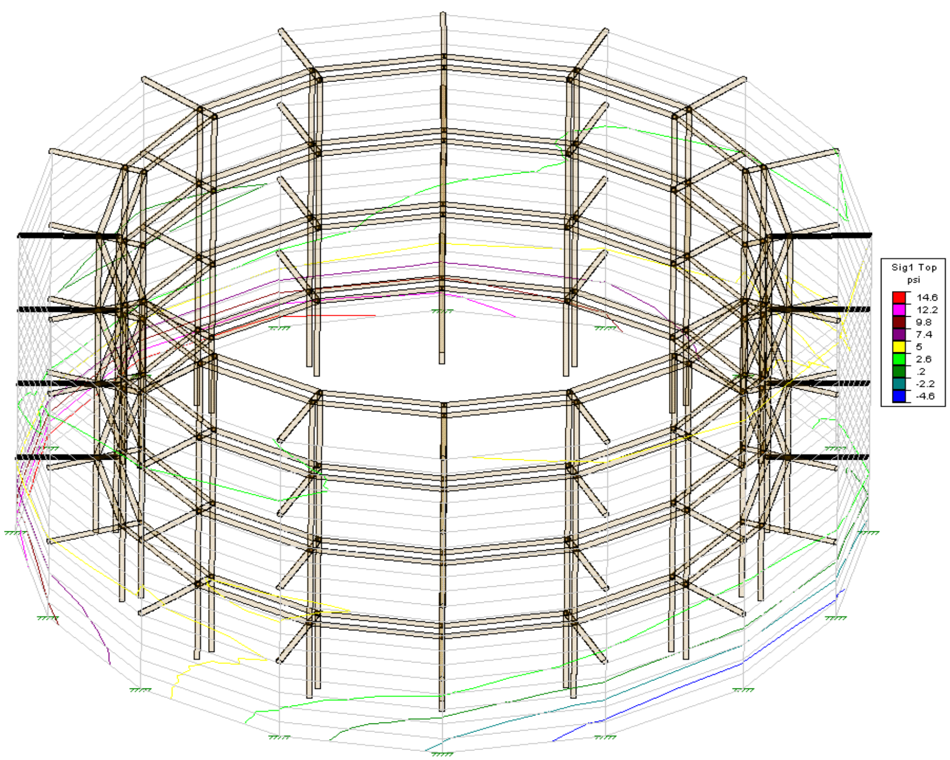
3-D Earthquake Load Animation for Tulou Under Most Conservative Scenario

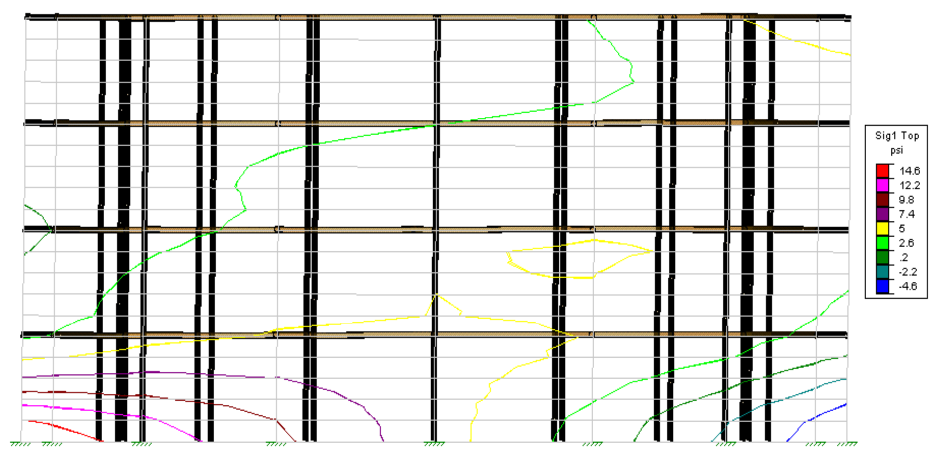


Huanji Tulou Model: RE Wall with Inner Wooden Structure



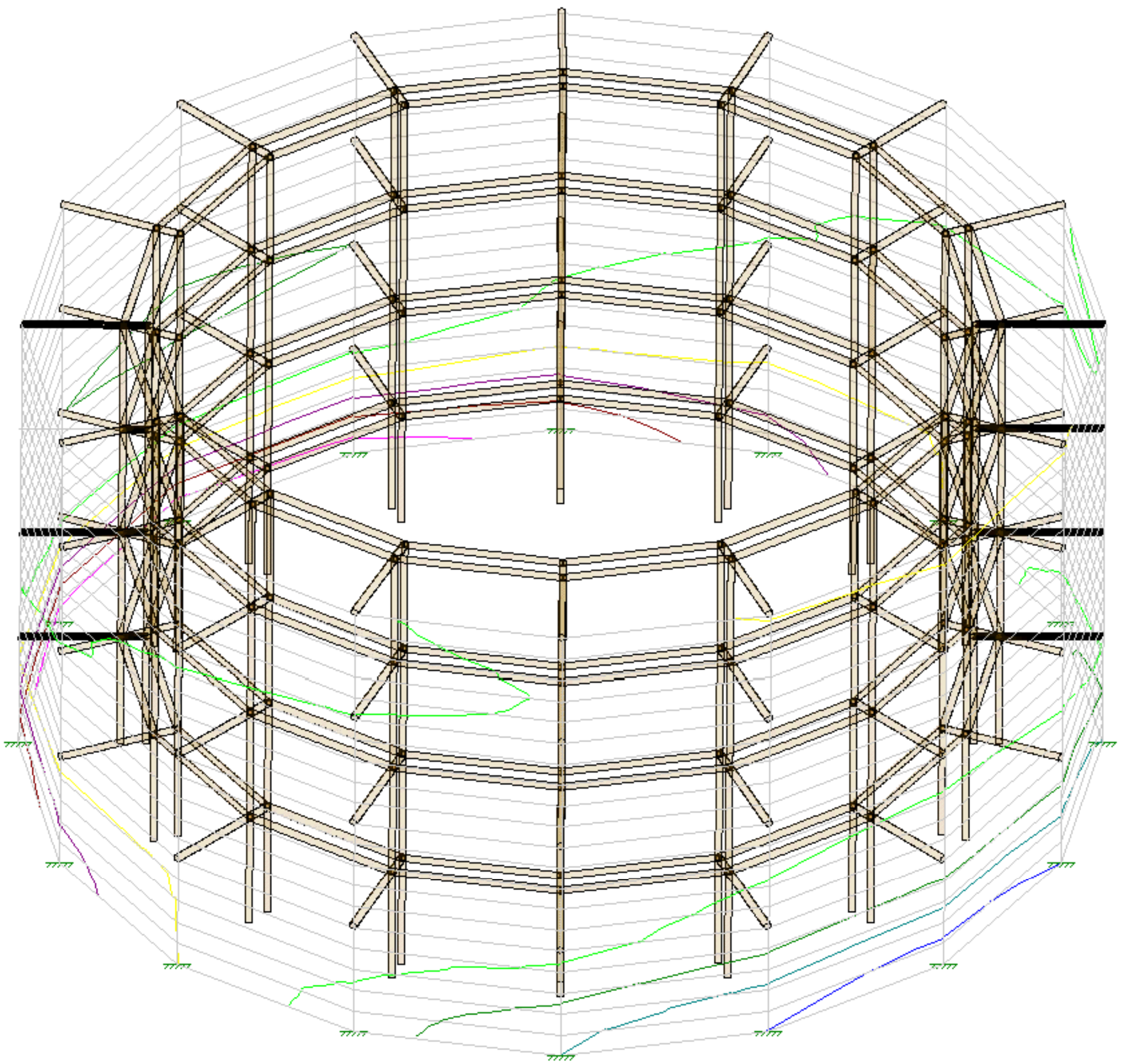
2D and 3D Stress Distribution of Huanji Model with Inner Wooden Structure





Material	E (psi)	Max Δ (m)
Weakest R. Earth	1706	0.2

3-D Earthquake Load Animation for Huanji Model with Inner Wooden Structure



Earthquake Resistance of Hakka Tulou

- The thick rammed earth wall has kept the stress low and away from the failure zone, under a quake induced load.

- The high mass of the Tulou structure has helped disperse the dynamic loads experienced by earthquakes.

- The RE wall coupled with inner wooden structure offers strong earthquake resistance.

- The shape change from square to circle Tulou also helps reducing stress concentrations offering additional earthquake resistance.

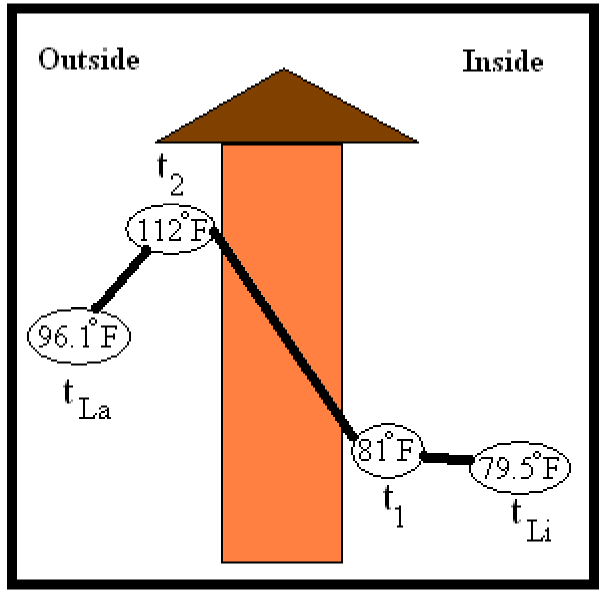
Climate Data of Chengqi Tulou

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		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

Relative 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



Schematic of the Chengqi Tulou Temperature Profile on a Summer Day

Thermal Comfort Analysis: Thermal Resistance

- k=0.91 $\frac{w}{m-k}$ $r=\frac{1}{k}$
- r=1.0986 $\frac{m-k}{w}$
- R=1.98 $\frac{m^2-k}{w}$ or 11.24 $\frac{ft^2-F^o-hr}{BTU}$
- R= $\frac{d\ (m)}{k\ (\frac{W}{mK})}$
- Thermal Resistance of rammed earth =R-0.16 per inch of material
- Similar to concrete=R-0.10
- Polyurethane foam=R-7.70

Thermal Conductivity k, $\frac{w}{m-k}$

Softwood =0.13
Rammed Earth =0.91
Concrete =1.0
Steel =55

Thermal Comfort Analysis: Thermal Mass

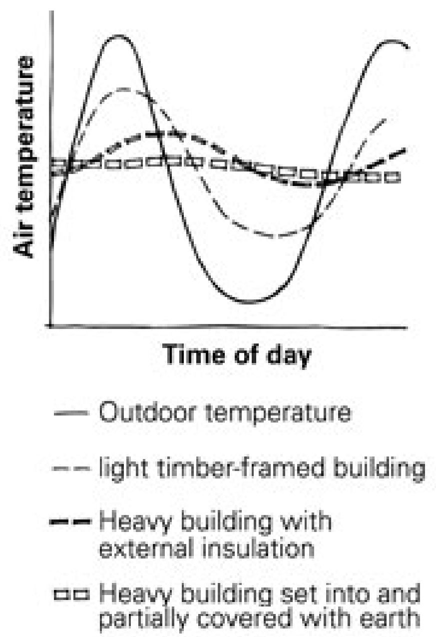
$$Q = C_{th*}\,\Delta T$$

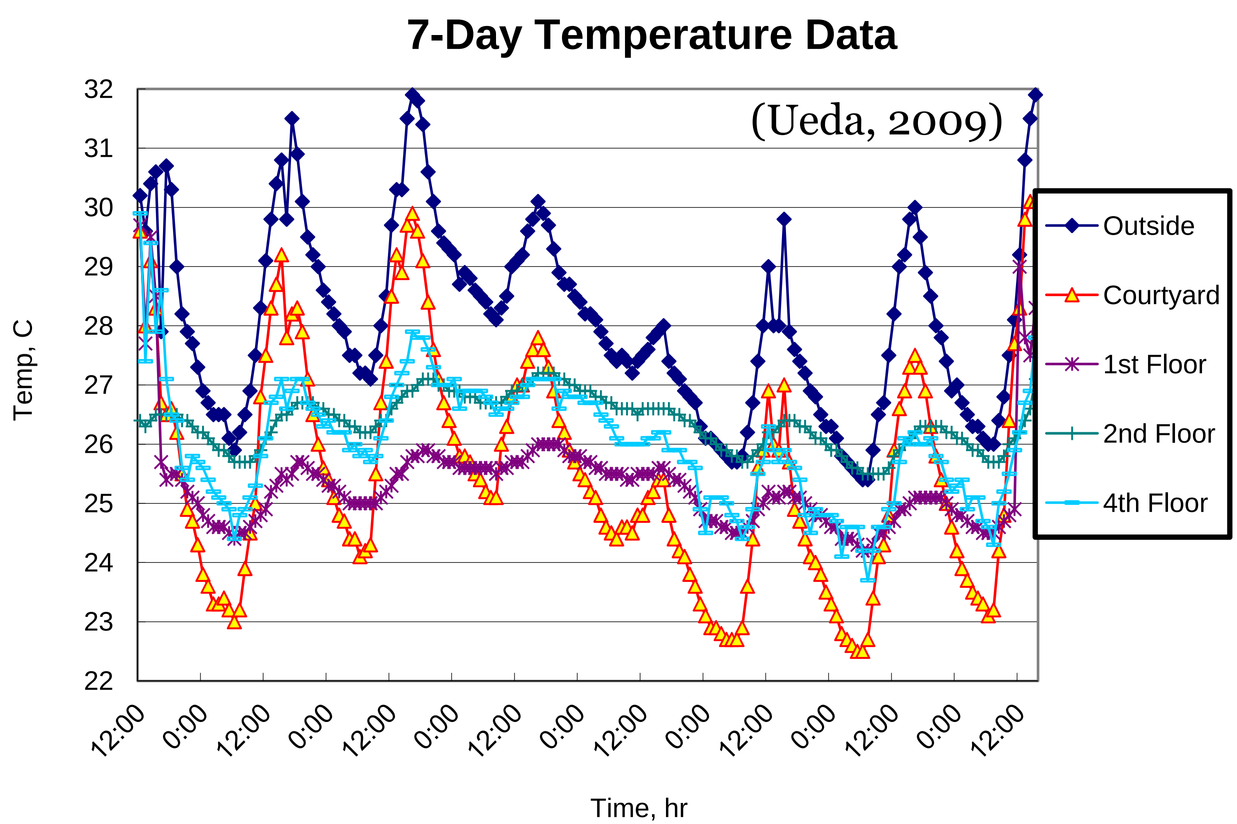
Thermal mass, $\frac{KJ}{m^3 - k}$

- Softwood=866
- Rammed Earth=1,673
- Concrete=2,060
- Steel=3,744

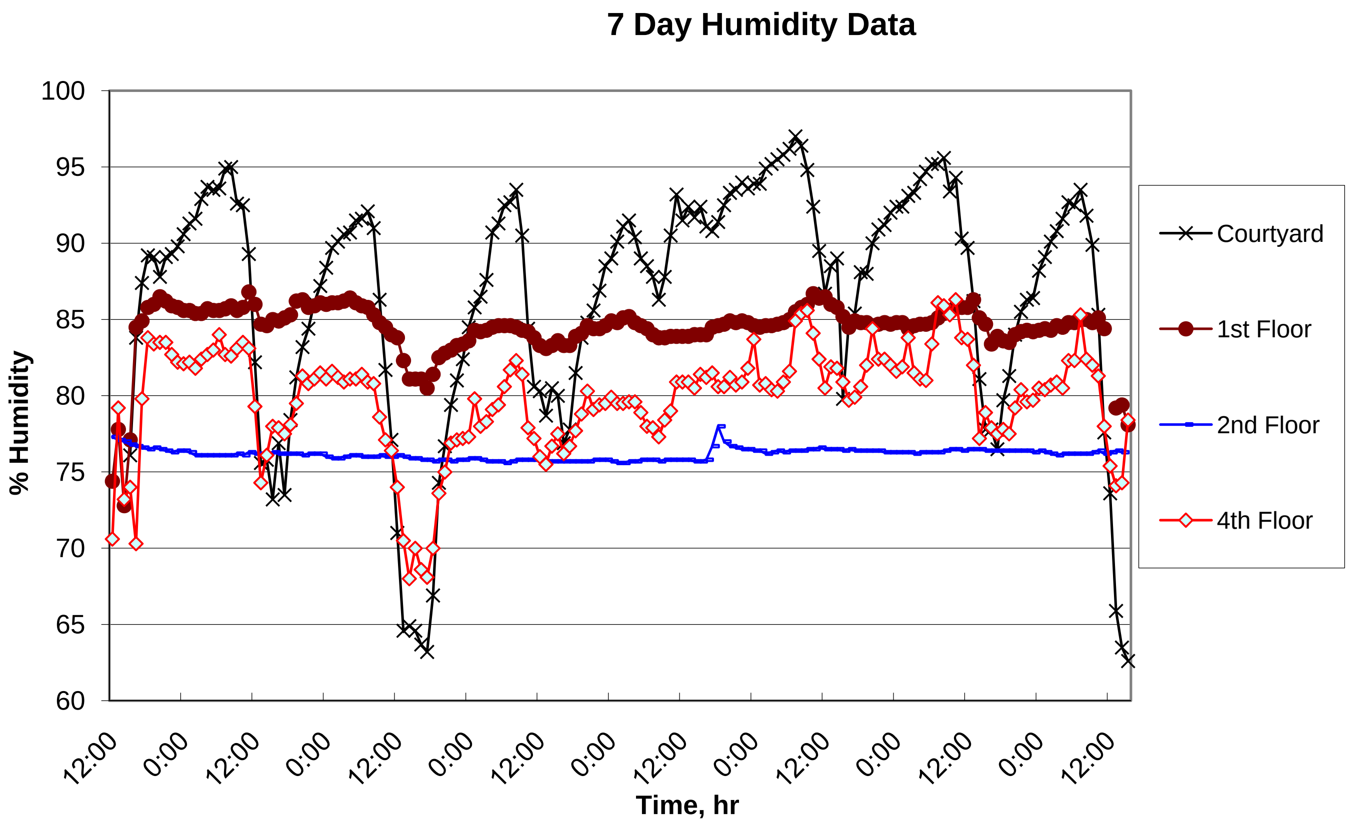
The Hakka people found ways to live in thermal comfort without the need of mechanical heating in winter or cooling in summer due to their effective use of rammed earth construction.

Chengqi Tulou 7-Day Temperature Data





Chengqi Tulou 7-Day Humidity Data



(Ueda, 2009)

What Have We Learned?

- Internal wooden system structurally sound
  - √ China-Fir (High Decay Resistance)
- Self-healing of crack most likely FALSE
- Strength of rammed earth dependent on composition NOT age
- Hakka Tulou rammed earth wall very high resistance to earthquakes
  - ✓ High volume dissipates lateral force
- Rammed earth very thermal efficient
  - √ High thermal mass/low thermal conductivity

Why is This Important?

- Most common building materials concrete/steel
  - √ Cement production accounts for 5-10% of World's CO_2 emission (Dodson 2006)
- Rammed earth, a viable building material option
- LEED certification
  - ✓ Based on: "energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts (What LEED 2010)."

How can we use this Information?

- Continue studies in controlled environments
- Combine composite elements with rammed earth construction
- Promote rammed earth building codes
  - ✓ New Mexico Earthen Building Code
  - ✓ NAREBA Code
  - ✓ ASTM E2392

Example of contemporary rammed earth construction
Source: http://inhabitat.com/beautiful-rammed-earth-home-celebrates-colorado-nature/