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

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Abstract

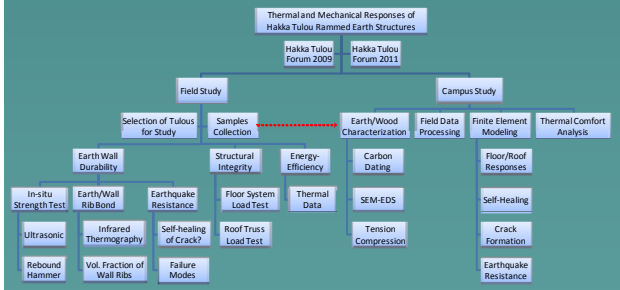
Hakka Tulous are rammed earth structures that have survived the material aging and natural weathering for over 1000 years. Through material and structural testing and evaluation, this study has examined the durability, structural integrity and living comfort of Hakka rammed earth constructions. The sustainability concepts utilized through Hakka Tulou construction and their benefits have been highlighted with reference to design and construction of future sustainable structures.

Objectives

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

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

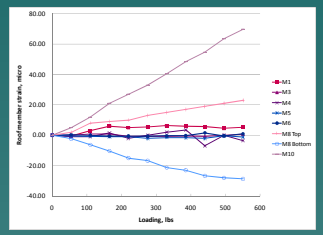
Scope of Work



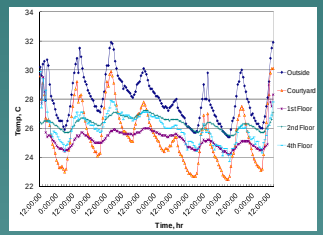
Tulous Studied: Fuxing (Square_2 Story_Built in 769); Wuyun (Sq_4 S_B 1500); Chengqi (Round_4 S_B 1709); Huanji (Ro_4 S_B 1693); Zhencheng (Ro_4 S_B 1912)

Results

Chengqi Tulou Roof Truss Member Strain Data



Chengqi Tulou 7 Day Temperature Data



Rammed Earth Compression Properties

Tulou	Age (years)	Xiamen University E (psi)	Xiamen University fc (psi)	WVU E (psi)	WVU fc (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

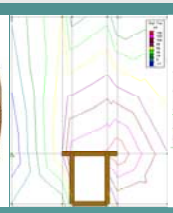
Load Sharing Effect of Chengqi Tulou Floor and Roof Members

	Floor System at 550 lbs: Structure Considered	Floor System at 550 lbs: Strain at Loading Beam (με)	Roof Truss at 550 lbs: Structure Considered	Roof Truss at 550 lbs: 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)

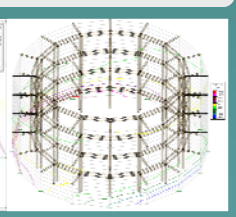
FE Modeling

Huanji Crack due to Quake

Crack Model and Thermal Expansion at 70F

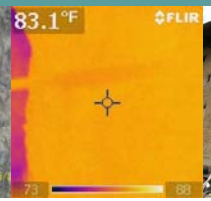


Stress near Lintel due to Horizontal Quake Load

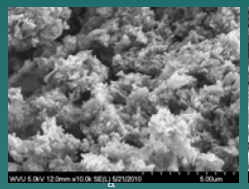


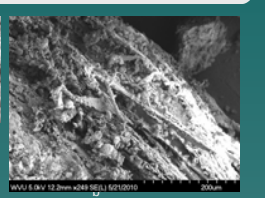
3D Earthquake Stress Distribution

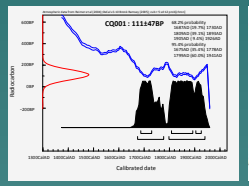
Field Study

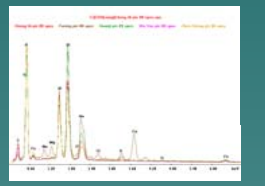


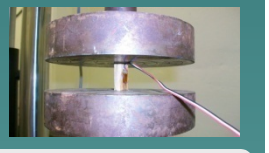
Earth/Wood Characterization











Conclusions

Hakka Tulous have excellent earthquake resistance. There is no self-healing of the quake-induced crack of Huanji Tulou. Fuxing Tulou's outstanding durability is due to abundance of calcium from lime in its earth wall formulation. NDT techniques such as ultrasonic were proved effective to quantitatively compare the strength of rammed earth walls. 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. Our findings may lead to using Hakka principles to build more disaster resistant structures and also shed light on new approaches applicable to LEED projects. Modern construction can simulate the Hakka construction techniques and make rammed earth construction a viable building material option of the future.

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