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LOCALIZATION STUDY, DEMONSTRATION AND EXTENSION OF UPGRADED RAMMED-EARTH TECHNOLOGY IN RURAL CHINA

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SUMMARY

Construction with earthen materials, one of the oldest traditional technologies, has been widely employed all over China in the past millennia. However, regarded as a symbol of “poverty” in recent years, more and more rammed-earth dwellings have been abandoned and replaced by conventional concrete and fired brick constructions. Unfortunately, these often poorly executed concrete-brick dwellings offer poor results in terms of comfort, anti-seismic capacity and sustainability, in connection with the limited economic, technologic and educational conditions within rural China.

Authorized by the Ministry of Housing and Urban-Rural Development of China (MOHURD), in 2011 a demonstration research project was launched by the Wu Zhi Qiao Charitable Foundation with the scientific support of CRATerre-ENSAG. Based on the innovation and improvement of local traditional rammed-earth technology, it aims to illustrate an affordable, sustainable and ecological way to construct rural dwellings, which could be adopted and passed on by villagers in regions where rammed-earth construction is traditionally practiced.

With the village of Macha (Gansu Province) as the starting point, earth-material science and its related technical theories were first identified and tested through a series of adapted experimental and practical studies. Promoted by MOHURD, by 2016, research outputs have been successfully extended to 10 other regions.

INTRODUCTION

The use of earth as a construction material has a long history in rural China. According to the latest statistics (NBSPRC, 2012), at least 60 million people in China are still living in traditional rammed-earth dwellings, most of which are located in poor and rural regions (fig. 1). In recent decades, due to the fact that earth-based building technologies are usually regarded as “dangerous” and perceived as a symbol of poverty by dwellers and governments, an increasing number of rammed-earth constructions have been abandoned and replaced by conventional constructions featuring concrete and bricks. However, limited by the low level of economic, technologic and educational conditions, most concrete and brick-based dwellings offer poor results in terms of comfort, anti-seismic capacity and sustainability. Authorized by the Ministry of Housing and Urban-Rural Construction of China (MOHURD), in 2011 a demonstration research project was launched by Wu Zhi Qiao (Bridge to China) Charitable Foundation with the scientific support from CRATerre-ENSAG.

Based on the innovation and improvement of traditional rammed-earth technologies, the project aims to illustrate an affordable, sustainable and ecological way to build in rural contexts, which could be adopted and passed on by villagers in regions with a rammed-earth construction tradition. After 4 years of experimental studies, a series of rammed-earth-based techniques and building tools and methods could be developed and adapted to local conditions, and were successfully extended to 10 regions of China through technical trainings programs based on demonstration construction activities.

1. BACKGROUND AND ISSUES

Various forms of traditional earthen dwellings are still being employed in almost all provinces of China. In most cases, the low level of economy is the core reason why those dwellings have survived till now.



Fig. 1 China's traditional earth architectures and distribution

However, after several catastrophic earthquakes since 2008, a large number of earthen houses were severely damaged, which resulted in disappointment from villagers and local governments due to the lack of resistance seen in traditional earth-based buildings. Building with concrete and fired-bricks is always regarded as the only reliable option, perceived as both “safe” and “modern”. Consequently, the central government of China, in the past decade, has worked towards providing poor rural regions with financial and political support to replace millions of “dangerous” earthen dwellings with conventional concrete and fired-brick constructions. However, the actual result is that most of these replacement buildings have become dangerous and energy-inefficient, since the only affordable and viable way to build for most villagers is to simply “combine” concrete-based techniques with traditional building principles.

In this context, the potential of rammed-earth as the most popular traditional earthen technology in China, could be analyzed through earth-based material scientific principles developed in other countries. However, due to the difficult conditions in rural China, successful practical experiences carried out internationally may not be directly applied to enhance the mechanical performance of rammed-earth dwellings in rural China. Thus, localized rammed-earth construction principles, which can lead to the implementation of affordable, earthquake-resistant and sustainable buildings, are much needed.

2. METHODOLOGY

The demonstration research project was first launched in Macha village, Gansu, where the rammed earth construction tradition has been present for thousands of years.

The action plan for the project was designed and implemented in three phases: 1) experimental studies on earthen materials, construction tools and construction methods; 2) prototype-based demonstration and regional extension; 3) cross-regional and training-based

extension together with diversified practices.

Firstly, concerning the disadvantages of traditional rammed-earth technologies in terms of mechanical and waterproofing performance, the theory of performance improvement of earth materials was first adapted to rural China. A number of rammed-earth-based techniques and construction tools and methods were upgraded by a series of experimental studies, and adequately enriched with ecological design strategies.

Secondly, based on the locally-available resources, experimental outcomes were further examined and improved through the construction of a housing prototype achieved by mobilizing local villagers. Trained and sensitized, 28 volunteer families in the region have rebuilt their houses through traditional self-organized construction strategies. More families are following these steps.

Supported by MOHURD, the demonstration study was extended cross-regionally. With technical support and trainings from the research team and the well-trained villagers from Macha village, over 110 rammed-earth prototype houses, integrating local building traditions and cultures, have been successfully constructed by local villagers in 10 provinces. To crystalize the cross-regional experiences and disseminate them among laymen such as villagers and carpenters, a DIY construction manual on upgraded rammed-earth technology was published. Meanwhile, several modern earthen architecture projects have been professionally constructed to further showcase that earthen architecture should not be underestimated.

3. FUNDAMENTAL RESEARCH

3.1. THEORY VERIFICATION AND STRATEGY ANALYSES

According to the theory of soil stabilization developed by CRA-Terre-ENSAG (Houben, 1994), the mechanical performance of rammed-earth mass could be greatly enhanced via powerful ramming and a gap-graded mixture of clay-sand-gravel with 8-12% moisture content. The theory was well verified by a series of material exper-



Fig. 2 Traditional shuttering systems of rammed-earth in China

periments with various samples of soil around the region. By providing a ramming force of over 0.5 MPa with the pneumatic hammer, the compressive strength of upgraded rammed-earth mass (40×40×150cm) reaches 1.4 MPa in average, almost twice the local traditional rammed-earth mass (Ying, 2012), even close to the one of China's conventional fired-brick walls.

Encouraged by the material experiment results, a comparative study between upgraded and traditional rammed-earth technologies was further developed in order to clarify the key effect factors which influence the performance of rammed-earth. As shown in table 1, among all factors influencing the construction method and the localization of the upgraded rammed-earth technology, the availability of the shuttering system suitable for the use of pneumatic hammers is the biggest challenge in terms of Rural China's situation and hence should be one of the most crucial elements to be taken into account in the coming experimental study.

Effect Factor	China's Traditional Rammed-earth Technology	Upgraded Rammed-earth Technology
Material	"Clayey" soil <i>Poor mechanical properties of materials and water resistance</i>	Mixture of clay, sand, gravels <i>Improved mechanical properties of materials and water resistance</i>
Moisture content	5-15%	8-12%
Hammer	Manual Hammer <i>Limited ramming force</i>	Pneumatic /Electrical Hammer <i>Firmer ramming force. It's available by retrofitting the pneumatic tamper which is conventionally used for mine construction in China</i>
Shuttering system	Rafter/Board <i>Simple but unstable</i>	Flexible and Stronger Shuttering System <i>shuttering system is needed to withstand the greater ramming force from pneumatic hammers</i>
Materials Blending	Manual <i>Low efficiency, much manpower</i>	Blender <i>Efficient</i>

Table 1 Comparison between upgraded and China's traditional rammed-earth technologies

3.2. SHUTTERING SYSTEM AND CONSTRUCTION METHOD

Rafter-strapped and board-based shuttering systems are most commonly employed in China's traditional earthen architecture (fig. 2). These systems, however, are not strong enough to resist the ramming force from pneumatic hammers, and are also not suitable in regions with limited timber resources. Considering for instance Northwestern China, as shown in fig. 3, the rural situation was scrupulously reviewed so as to define a series of principles for the design of new shuttering systems.

Based on market investigations and several rounds of testing experiments, a set of shuttering systems were developed with bamboo plywood, shape steel and tension screws which are comparatively cheap and available in most rural markets around China. The system is composed of 9 panels (fig. 3) which can be flexibly assembled by only two workers for ramming "I", "L" and "T" shaped walls directly, so as to not only satisfy various rural construction demands, but also effectively reinforce wall corners mechanically.

Utilizing the developed formworks, an on-site experimental construction project was conducted by the team and Macha villagers (fig. 4). Various conventional building elements present in local rural dwellings, such as foundations, windows & doors, openings, roofing, ring beams, etc., were combined into a housing prototype. The project not only aimed at testing the shuttering system for further improvement, but also served as an experience to learn from the lessons and even from the "mistakes" happening during rammed-earth construction. Through this process, the construction method with rammed-earth could be well developed and optimized with a series of feasible construction details for various components. It was

Fig. 3 Principles for developing a suitable shuttering system; the developed system

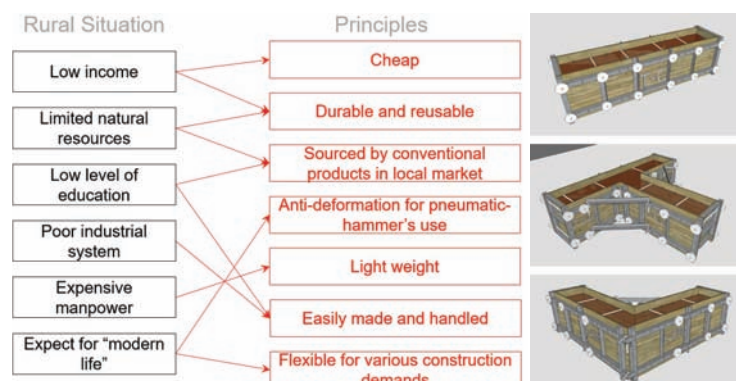




Fig. 4 On-site experimental construction



also verified, through a cost efficiency, construction efficiency and operability assessment, including the response from local villagers, that the upgraded rammed-earth technology is well adapted to local conditions and may thus be further disseminated.

3.3. REINFORCEMENT OF STRUCTURE SYSTEM

A specialized building code for earth-based construction is not available in China. Since the Wenchuan earthquake of 2008, the National code for earthquake-resistant rural masonry-structure dwellings has been upgraded. In this context, a scientific study on the structural system of new rammed-earth dwellings seems crucial to ensure future dissemination. Both systems (traditional rammed-earth building and masonry structure with codes) were carefully reviewed, as were the mechanical properties of upgraded rammed-earth walls together with the developed construction methods. A series of feasible technical tests for the reinforcement of rammed-earth dwellings were carried out and could be summarized in three aspects:

1) Wall span, storeys and floor height of rammed-earth structures to reach a reasonable shape coefficient for seismic resistance; 2) involvement of timber-made (or prefabricated concrete) structural columns in wall corners and ring beams (timber or prefabricated concrete) on both the top and bottom portions of earth walls; 3) improving structural measures for joints between walls, roofs and walls, and foundations to further enhance structural integrity.

In order to further verify the performance of integrated systems, two models (4 m by 4 m on plan) with two conventional roofing systems (concrete-based flat roof and timber-based sloping roof) were built for shaking-table experiments. The shaking simulation result shows that the two systems work well and reach Chinese demands for 8.5-magnitude seismic resistance. According to further calculation and analyses, it is verified that in terms of the anti-seismic performance, rammed-earth (load bearing rammed-earth walls, less than

3-storey high) with a well-designed structural system works well in most regions of China. Authorized by MOHURD, the team is drafting the National code on rammed-earth dwellings based on experimental data (fig. 5).

4. DEMONSTRATION CONSTRUCTION AND REGIONAL EXTENSION

A new rammed-earth courtyard for an old couple, as a prototype, was constructed by local masons and villagers under the guidance of the team. (fig. 6) The project provided them with participative training on the basic techniques, allowing for participants to directly experience new construction techniques and learn how to build by themselves. During the process, research results and construction experiences were further consolidated by the team through the creation of an easy-to-follow technical guide aimed at local populations. Taking local culture and customs into account, the team studied the traditional courtyard pattern and carried out a number of design proposals to be applied selectively in house rebuilding projects, according to individual conditions and needs.

Convinced by the prototype's performance, all 12 families in Macha village, who were granted the opportunity to renew their housing in 2013, decided to opt for the new rammed-earth construction technologies. Equipped with the guide, design proposals and more importantly, empowered through their active participation in the construction of the prototype, the families built their own houses over a period of three months. It came as a surprise that villagers clearly showed their creativity and wisdom as designers and builders. After all, they knew best about their own lives and needs.

Fig. 5 Improved structural system and models for shaking-table experiments





Fig. 6 The first rammed-earth prototype built in Macha village

5. DIY MANUAL AND CROSS-REGIONAL EXTENSION

Based on previous experimental and demonstration studies, a DIY construction manual (Mu, 2014) on the construction of upgraded rammed-earth dwellings was published in 2014. All related techniques were summarized and illustrated with photos and drawings so as to be easily understood and applied by rural dwellers and artisans. The publication has been distributed by MOHURD in regions where rammed-earth construction is an element of the local building culture. With the help of the DIY manual and on the basis of the training sessions that took place in Macha, over 400 craftsmen in Gansu Province could be trained.

Promoted by MOHURD, more than 10 provincial governments have visited Macha village, showing great interest in the upgraded rammed-earth technology. Authorized by MOHURD and invited by said local governments over the past two years, 110 rammed-earth houses (partly as demonstration projects) have been built in 10 regions of China (fig. 7). During the process, further localization efforts were carried out, and combined with the implementation of updated build-

ing technologies, taking into account local traditions and needs. For each demonstration, 2 well-trained villagers from Macha and 1 professional from the team jointly guide the group of builders and provide on-site training to local villagers. To date, 23 villagers from Macha village have been well trained as trainers, and their livelihood was also improved by building earth houses.

According to observation and to statistics on the houses built in various provinces, the construction cost of new rammed-earth dwellings represents on average 2/3 of the cost of local conventional houses built with fired-bricks and concrete. When built with the assistance of neighbors, construction costs can get as low as 1/4 of the cost of conventional structures. Moreover, the embodied energy and CO₂ emission of the former amount to only 25% and 20% of the latter respectively. The ecological and economical potential of upgraded rammed-earth technologies is clearly illustrated through all cross-regional demonstration constructions. Informed and convinced, a growing number of governments and clients are actively asking for technical support. The cross-regional extension work has also drawn a lot of attention from China's mainstream media.

Fig. 7 Distribution of demonstrative constructions and regional impacts





Fig. 8 Vanke landscape project with rammed-earth, Xi'an

CONCLUSION

A large amount of experimental studies have gradually proved that the innovation of traditional architecture based on the use of locally available resources is the most viable and effective path for the development of China's rural construction, ecological architecture and the preservation of cultural heritage. Scientific theories were adequately combined with inventory studies through the effective cooperation between CRATerre-ENSAG and the team. A methodology based on the "high science and low technology" principle needs to be highlighted and well followed so as to ensure that research results are used, adopted and passed on to local populations.

Today, through more and more demonstrative earth-based projects supported by professionals, a wider dissemination and promotion of results and the increased attention given by China's central government concerning tradition heritage, it becomes much clearer that local governments, clients, architects and even the general public are starting to acknowledge the value of earth architecture as a cultural heritage and for its potential in sustainable development. The question changed from "why earthen architecture?" to "how?", which is a positive shift that occurred more quickly than expected by the team 5 years ago.

However, there is still a long way to go. Recently when asking villagers to describe newly-built rammed-earth houses, they commented on their solidity and comfort but also remarked that "they still look like earth". In their mind, the association between "earth" and poverty remains. Therefore, the team is now also trying to apply upgraded rammed-earth technologies into modern earth architecture projects, such as the Vanke landscape project (fig. 8) and the Macha village center (fig. 9), so as to showcase what the future of earth architecture could be. However, much work remains to be done to change the image of earthen architecture in people's minds. What the team has accomplished is a start. The vast field of research that is earthen

architecture needs to pursue efforts towards more systematic and sustainable studies and practices, with more parties involved.

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Fig. 9 Macha village center in Macha village, Gansu

