Analysis of the Structural Characteristics of Rural Residential Buildings in Hainan Province

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Abstract. Most of the rural houses in Hainan Province are self-built by the residents, and due to the constraints of geography, economic conditions, and professional technology, many houses have problems such as poor construction quality, low strength of materials, and no anti-seismic precautions, which result in poor seismic capacity of the houses and make them susceptible to serious damage in case of earthquakes. Through the field survey, there are mainly stone-wood structures, brick-stone mixed structures, brick-wood structures, brick-concrete structures, frame structures and other structural types of houses in Hainan Province, which can be roughly divided into four categories according to the construction age. This paper analyzes the structural characteristics and seismic weaknesses of township houses of different construction ages in Hainan Province, intending to provide theoretical value to the seismic defense and subsequent reinforcement of township houses in Hainan Province. The results show that the houses in the township areas of Hainan Province are mostly masonry structures, and there are a large number of old masonry structures. Among them, the stone-wood structure, brick-stone mixed structure and brick-wood structure are almost not equipped with structural measures, and there is only biting masonry between the transverse wall and the longitudinal wall. The seismic performance of these buildings is relatively poor, and they are vulnerable to damage when they encounter local fortification-intensity earthquakes.

Keywords: Hainan; township rural houses; seismic performance; sampled detailed inspection of building construction

1 INTRODUCTION

Agricultural buildings in China's rural areas are affected by many aspects of the construction process, including climatic conditions, economic development, ethnic customs, craftsmanship, and so on, which results in the existence of uneven construction quality and incomplete anti-seismic construction measures. The seismic capacity of these buildings varies, and most of the anti-seismic structural measures are incomplete,

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which makes rural buildings basically in a state of no fortification or poor fortification. Once an earthquake occurs, they are vulnerable to serious damage.

In recent years, devastating earthquakes, such as the Wenchuan earthquake, the Jiuzhaigou earthquake, the Luding earthquake, and so on, have once again revealed the weak seismic capacity of rural houses in China [1]. Taking the 6.8 magnitude earthquake that occurred in Luding County, Ganzi Prefecture, Sichuan Province on September 5, 2022 as an example, the earthquake killed 93 people, 25 people lost contact, more than 270 people were injured, more than 110,000 people were affected, and more than 50,000 houses were damaged. Most houses in China's urban areas consider seismic fortification during construction. However, the rural areas are relatively backward, and most of the residents ' self-built houses do not consider the structural measures or the structural measures are incomplete, so these earthquakes often cause severe damage to the rural areas, and even in the VI degree area, there are serious damage to the buildings [2].Therefore, how to identify the structural characteristics of different types of rural residential buildings and analyze the seismic capacity in combination with these characteristics is very important to improve the seismic performance of rural residential buildings in China. At the same time, the results are of great significance for assessing the risk of earthquake disasters and guiding the seismic strengthening work.

Hainan Province is located at the southwest end of the seismic belt on the southeast coast of China. The area starts from the coast of Fujian Province in the east and extends to the North Bay in the west. This region has a high risk in terms of earthquake geology and tectonics, especially in the northern part of Hainan Province, where there is a tectonic background for strong earthquakes to occur. In the history of Hainan Province, there have been many destructive earthquakes in Hainan Province, most of which are concentrated in the northern part of Hainan Province. There are 20 earthquakes with $M \geq 6$, the largest of which is the 7.5 magnitude earthquake near the Dongzhai Port at the junction of Qiongshan and Wenchang in Hainan Province on July 13, 1605 [3]. It caused hefty casualties and house damage in Qiongshan and Wenchang, and the whole of Hainan Island was affected to varying degrees [4].

According to the ground motion parameter zoning map in 2015 (Figure 1), the highest seismic fortification intensity in Hainan Province is 8 degrees. The 8-degree area is mainly located in the northeastern part of the province, including the surrounding area of Haikou City. This is a more economically developed and densely populated area in Hainan Province. The vast majority of township areas are located in 7-degree and 6-degree areas.

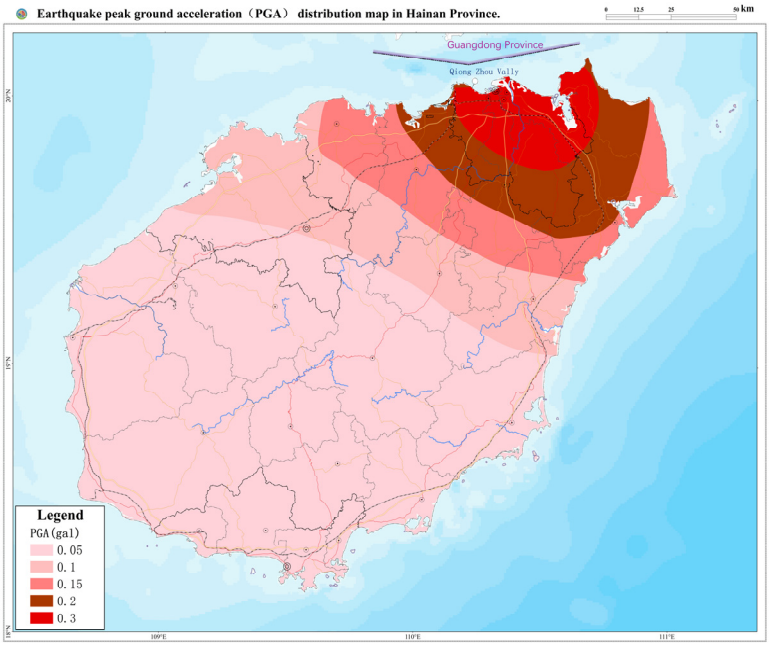

Fig. 1. Earthquake peak ground acceleration（PGA） distribution map in Hainan Province.

The rural areas of Hainan Province account for a large proportion, with a vast territory and a large population. The Han, Li, and Miao are the native ethnic groups in Hainan Province. The ship house is the oldest rural residential building of the Li ethnic. The Miao ethnic, a guest ethnic group that migrated to Hainan in the middle and late Ming Dynasty, has great flexibility in its traditional rural houses. The common Miao houses in Hainan Province are mostly tree houses or dry-column thatched houses [5]. With the development of the economy, buildings such as boat houses, tree houses, and dry-column thatched houses have long been a history, and civil structures, brick-wood structures, and brick masonry structures have emerged.

These existing civil structures, stone-wood structures, and other rural materials have low bond strength, almost no seismic fortification measures, and poor structural integrity. There is a seismic geological structure background of strong earthquakes in Hainan Island, so there are certain seismic disaster risks and hidden dangers in township areas of Hainan Province.

Earthquake disaster risk survey is the basic work of earthquake disaster prevention and control. The research goal of this paper is to investigate and find out the structural characteristics and seismic weak links of township rural houses in different construction years in Hainan Province, further improve the reliability of earthquake disaster risk assessment in Hainan Province, and provide theoretical value for seismic fortification and subsequent reinforcement of township rural houses in Hainan Province. This paper conducted a detailed sampling survey of rural houses in Hainan Province and analyzed the characteristics of their building structures. Based on field investigation, rural houses

can be divided into five categories according to the structure type: stone-wood structures, brick-wood structures, brick-stone mixed structures, brick-concrete structures, and frame structures.

Different structural types of rural houses were built in different periods, and most of the stone-wood structures were built before 1990. The brick-wood structure and brick-stone mixed structure were mainly built between 1990 and 2000; the brick-concrete structure was built from 2000 to 2010; the frame structure appeared after 2010. Then, this paper analyzes the structural characteristics of different types of rural houses, summarizes their weak seismic links, in order to grasp the current situation of seismic capacity of existing houses in villages and towns, gives the survey conclusions and puts forward corresponding seismic suggestions.

2 SURVEY POINTS OVERVIEW AND SURVEY CONTENT

2.1 Research Methodology and Survey Points Overview

Hainan Province, with a total land area of 35,400 square kilometers, is located in the southernmost part of China and has a tropical monsoon climate. The Han, Li and Miao are the native ethnic groups in Hainan Province. According to the results of the Seventh National Population Census, the total population of Hainan Province is 10 million 812 thousand, of which the rural population accounts for 39.73 % [6].

This paper mainly adopts the research method of sampled detailed inspection of building construction. In the face of the large stock and wide distribution of typical villages and towns in Hainan Province, according to a specific sampling statistical method, a certain amount of samples are randomly selected, and the selected samples must be representative. The detailed sampling survey of buildings is one of the basic work in earthquake disaster risk assessment, and it is an indispensable data source for establishing a scientific and reliable building vulnerability model.

According to the local census information obtained from the relevant departments and the on-site survey of UAV aerial photos, the proportion of different structural types in each survey site can be obtained, and then the proportion of different building types in Hainan township areas can be calculated. Combined with the general structural characteristics of each type of building, the seismic weak link analysis is carried out. The technical roadmap of the seismic capacity survey of buildings is shown in Figure 2.

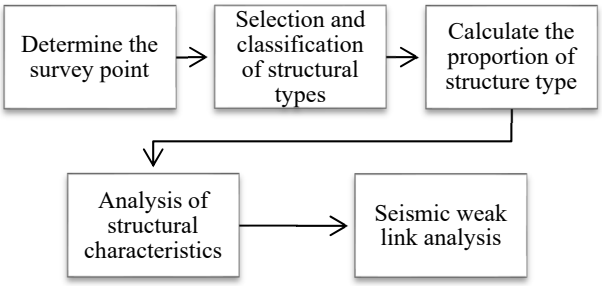

Fig. 2. Technical roadmap for building seismic resistance capability investigation.

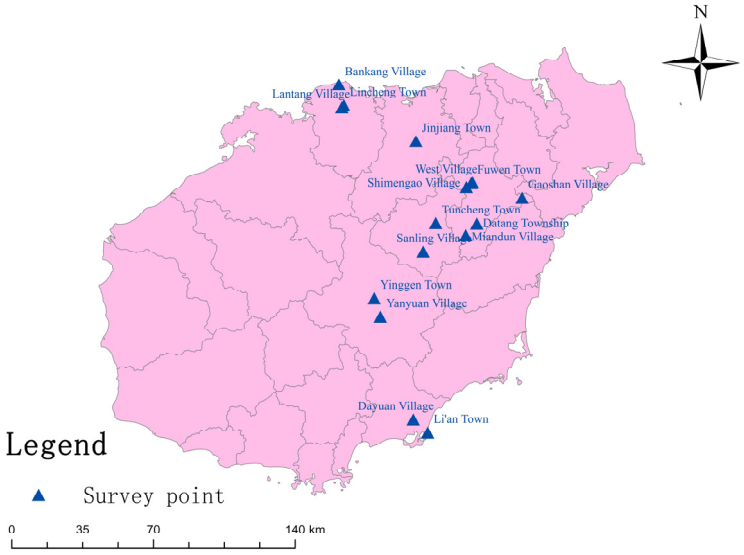

Fig. 3. Distribution of investigation area

In this paper, six towns, nine villages and one township in six counties of Hainan Province were selected as survey points. The selection of each survey site follows the following principles: 1. the survey area should cover houses built in different ages; 2.the survey area should cover houses with different fortification requirements, covering houses built by self-built and regular design and construction; 3.the survey area should cover different seismic fortification intensity areas; 4.the buildings of the survey site can represent the construction characteristics of a large number of buildings in the township area of Hainan Province.

Based on the above principles, while following the principle of balance and typicality, the distribution of survey points selected in this survey is shown in Figure 3. Each survey point is divided according to the intensity as follows :

8-degree area: Fuwen Town, Shimengao Village, Gaoshan Village, West Village, Mandun Village, Datang Township in Ding 'an County.

7-degree area: Lincheng Town, Bankang Village, Lantang Village in Lingao County, Jinjiang Town in Chengmai County, Tuncheng Town, Sanling Village in Tunchang County.

6 -degree area: Yinggen Town, Yanyuan Village in Qiongzhong County, Li 'an Town, Dayuan Village in Lingshui County.

2.2 Investigation Content

On-site sampling and detailed investigation of buildings were carried out to investigate the structural types, structural measures, foundation types, mortar strength, roof forms, and construction ages of various rural houses. The houses built in the same period in the township areas of Hainan Province have similar construction materials, construction techniques, and structural forms. The characteristics of building structure are highly correlated with the construction age, while the houses of different ages are quite different. Therefore, according to the construction age, the rural houses in the township areas of Hainan Province are simply divided into four categories :

2.2.1Rural Houses Built Before 1990.

This kind of structure is mostly stone-wood structure, and the number of layers is generally single layer (Figure 4a)). It accounts for about 9 % of the township survey area of Hainan Province, and there are still residents living or using it. This kind of structure uses volcanic stone as masonry material after processing, and the roof truss is a wooden roof truss, which is called the 'tile-roofed house ' by residents, and no structural measures are set up.

a) **b)**

Fig. 4. Stone-wood structure rural house and its aerial photography

The stone-wood structure accounts for a large proportion in the economically poorer areas and a relatively low proportion in the more affluent areas. Among the survey points, the number of stone-wood structures in Bankang Village, Lantang Village in

Lingao County, and Sanling Village in Tunchang County accounted for more than 40 %. Figure 4 b) shows an aerial photo of the village in the field survey. The buildings in the red box are all stone and wood structures built before 1990.

2.2.2 Rural Houses Built Between 1990 and 2000.

Due to the development of the economic level, the buildings in this period gradually began to use sintered clay bricks to build walls. However, the amount of brick is not much, and many houses are brick-stone mixed structures(Figure 5). The common structural forms include brick-stone mixed structure and brick-wood structure, both of which are single-layer. The total proportion in the survey area is about 33 %. The brick-stone mixed structure adopts volcanic stone as the masonry material of the lower wall, the upper part of the wall is made of sintered red brick, and the roof truss is a wooden roof truss. Brick and wood structures all use sintered bricks as masonry materials.

a) **b)**

Fig. 5. Brick-stone mixed structure and the aerial photography of brick-wood structures in Shimengao Village

2.2.3 Rural Houses Built Between 2000 and 2010.

With the improvement of the economic level and the development of construction technology after 2000, most of the rural houses built in this period adopted brick-concrete structures, and the number of building layers was mostly 2 ~ 3 layers, accounting for about 40 % in the survey area. According to the different construction times and the difference of government-led policies in different regions, such structures are divided into two types: structural measures and non-structural measures.

In each survey point, compared with the village, the economic development of the town is better, and the brick-concrete structure in the town accounts for a larger proportion. In the red box of Figure 6, the brick-concrete structure houses near Hongwei Street, Lincheng Town, Lingao County, were built between 2000 and 2010. The number of brick-concrete structures in this area accounted for 60.09 %.

Fig. 6. Aerial photo of brick-concrete structures in Lincheng town, Lingao County

Fig. 7. Aerial photo of frame structures of Sanling village, Tunchang County

2.2.4 Rural Houses Built After 2010.

With the development of the economic level, after 2010, most of the new farmers in the township areas of Hainan Province were frame-structured houses, accounting for about 18 % of the total in the survey area. Most of these structures are self-built houses with 2-3 floors, and the exposed column steel bars are retained and rust-proofed on the top floor so that the residents can cover the floors when they are more affluent in the future.

The white flat-roof houses in Figure 7 are frame structures, which are newly built buildings in Sanling Village, Tunchang County, accounting for 43.84 % of the total number of buildings in the village.

Based on the investigation and analysis, the proportion of each structural building in the sample survey area is determined as shown in Table 1. According to the results of the survey, due to the better economic development level in urban areas of Hainan Province than in rural areas, there is almost no stone-wood structure with a long history of construction, and the proportion of brick-stone mixed structure is also low. Similarly, because urban areas develop faster than rural areas, frame structures and brick-concrete structures account for a large proportion.

Table 1. The proportion of buildings with various structures in the investigation area (unit: %).

investigation point	stone-wood structures	brick-stone mixed structures	brick-wood structures	brick-concrete structures	frame structures
Lincheng Town, Lingao County	——	——	1.65	60.09	38.26
Bankang Village, Lingao County	47.59	12.02	2.81	30.34	7.24
Lantang Village, Lingao County	41.18	3.53	7.06	37.64	10.59
Jinjiang Town, Chengmai County	1.32	——	2.46	78.25	17.97
Yinggen Town, Qiongzhong County	——	——	0.08	69.87	30.05
Yanyuan Village, Qiongzhong County	——	17.81	3.42	73.97	4.80
Tuncheng Town, Tuen Chang County	0.67	——	0.26	75.37	23.70
Sanling Village, Tunchang County	45.88	4.78	2.08	3.42	43.84
Fuwen Town, Ding 'an County	1.32	——	0.62	81.06	17.00
Shimengao Village, Ding 'an County	14.80	7.66	68.94	8.60	——
Gaoshan Village, Ding 'an County	17.70	10.60	19.80	51.90	——
West Village, Ding 'an County	82.00	——	——	——	18.00
Miandun Village, Ding 'an County	20.50	17.12	31..78	22.70	7.90
Datang Township, Ding 'an County	——	84.30	——	9.42	6.28
Li 'an Town, Lingshui County	12.56	39.27	——	30.28	17.89

Dayuan Village, Lingshui County	——	6.19	12.37	38.14	43.3

3 THE ARCHITECTURAL AND STRUCTURAL CHARACTERISTICS OF RURAL HOUSES IN HAINAN PROVINCE

The township dwellings of each survey point were investigated by taking photos of the whole and local houses, finding relevant local information, asking residents, and on-site measurements. The research content of the residential houses in the investigated area mainly includes the proportion of various structures, the construction age, masonry materials, construction quality, structural characteristics, structural measures, and other basic conditions.

Based on the results of field investigation, according to the construction age of rural houses in township areas of Hainan Province, the general representative characteristics of residential buildings are selected to form the survey results of the seismic performance of buildings. The specific survey results are shown in Table 2. The building, structural characteristics and seismic weak links of rural houses with different construction years are analyzed respectively.

Table 2. Investigation results of rural buildings in township areas of Hainan Province.

Age of Construction	Before1990	Between1990-2000		Between 2000-2010	After2010	
Structural type	stone-wood structure	brick-stone mixed structure	brick-wood structure	brick-concrete structure	brick-concrete structure	frame structure
Foundation type	strip footing	strip footing	strip footing	strip footing	strip footing	independent footing
Thickness of load-bearing wall	200/150mm	180mm	180mm	240mm	240mm	——
Thickness of non-load-bearing wall	180/120mm	180/120mm	180/120mm	240/180mm	240/180mm	240/180mm
Mortar type	mud	mud	cement mortar	cement mortar	cement mortar	cement mortar
Strength of mortar	worse	worse	worse	well	well	well
Ring beam, constructional column	not set	not set	not set	Mostly set	set	——

Roof type	double-slope roof	double-slope roof	double-slope roof	flat roof	flat roof	flat roof
The connection mode of the gable wall and roof truss	purlin-on-wall flush-gabled roof	purlin-on-wall flush-gabled roof	purlin-on-wall flush-gabled roof	——	——	——
Roof truss material	timber truss	timber truss	timber truss	——	——	——
Roofing materials	Chinese style tile	Chinese style tile	Chinese style tile	cast-in-place concrete	cast-in-place concrete	cast-in-place concrete

Combined with the data of the local census in Hainan Province, the housing area of each building type in Hainan Province according to the census content is as shown in Table 3 :

Table 3. Percentage of building area of different structural types in Hainan Province.

Structure type	Masonry structure	Frame structure	high-rise structure	Single-layer structure	Other structure
The proportion	21.2%	70.6%	1.9%	0.3%	6%

Due to the different statistical methods of local data, stone-wood structure, brick-wood structure and brick-stone mixed structure are all counted into the single-layer structure, while brick-concrete structure is divided into masonry structure. The overall construction area of the single-layer structure in Hainan Province in Table 3 is relatively small, mainly because these houses built in the early years are single-layer buildings, the area is small, and most of them are distributed in rural areas. The number of buildings in rural areas is very small compared with other structural types of houses that are closely distributed in urban areas. However, in fact, in rural areas, stone-wood structures, brick-wood structures and brick-stone mixed structures still have a high number of buildings. In addition, masonry structure has a certain proportion in Hainan Province, and in recent years, most of the new houses are frame structures, which account for a relatively high proportion, reaching 70.6 %.

3.1 Rural Houses Built Before 1990

3.1.1 Architectural Features.

As one of the four major volcanic clusters in China, Hainan Province has more than 100 volcanoes in its northern region. Due to this unique geology, most of the stone-wood structures built before 1990 in Hainan Province were made of local materials, using volcanic stones to build walls and clay as masonry mortar (Figure 8). The beam, column, and roof truss are made of wood, and the foundation also uses volcanic stone as the material. Although its area accounts for a small proportion of the province, such buildings are still widely distributed in rural areas of Hainan Province. The stone-wood structures are almost single-layer buildings, and the building planes are mostly rectangular or square. The gable generally does not have windows, and the longitudinal wall

is generally equipped with 2 to 4 windows, with a window width of 0.5 m and a height of 0.8 m. The depth of the house is about 3m, and the width of the room is from 4m to 10m.

The masonry materials of stone-wood structures are mostly volcanic rocks excavated by residents in situ. The modulus is different from that of ordinary sintered bricks used in recent years. Therefore, the wall thickness of stone-wood structures is different from that of brick masonry structures, such as 240 mm and 180 mm. The wall thickness of the stone-wood structure is mostly 300 mm. The roof is a double-slope roof, and the roof structure is a purlin-on-wall flush-gabled roof. The roof material uses small green tiles, which are called ' tile houses ' by residents (Figure 9).

Fig. 8. Stone-wood structure of Hainan Province

Fig. 9. Detailed drawing of the Chinese style tile on the top of the stone-wood structure in Hainan Province

3.1.2 Structural Features.

The volcanic stone masonry blocks used in stone-wood structures in Hainan Province are not exactly the same as the modulus of ordinary sintered bricks due to their

long age and limited by the excavation process. The modulus was measured to be about 200mm × 130mm × 42mm during the field investigation (Figure 10).

Most of the stone-wood structures in Hainan Province use stone walls as vertical load-bearing members. Because the roof forms are mostly purlin-on-wall flush-gabled roofs, they are mainly supported by transverse walls; the roof truss is a wooden roof truss, and the wooden beam is used as a horizontal bearing member. The mortar used in the masonry of the stone wall is mud, which is mostly mixed with laterite and white lime, and the strength of the mortar is lower than M2.5. The vertical and horizontal walls are connected by interlocking masonry as a connection method, and there are no ring beams or constructional columns. The foundation adopts a strip foundation built of volcanic stone.

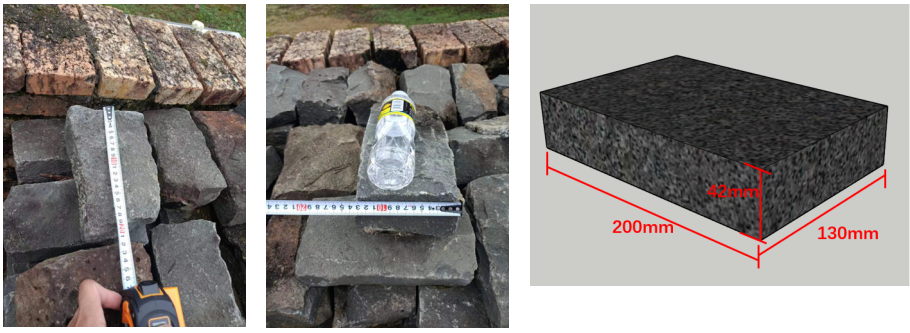

Fig. 10. Stone masonry module in Hainan Province

Fig. 11. Schematic diagram of stone-wood structure interlocking masonry in Hainan Province

3.1.3 Seismic Weak Links.

The stone-wood structures in Hainan were built earlier, mostly before 1990, and the masonry materials were volcanic stones. There were no ring beams and construction columns, and the integrity of the houses was poor. In addition, the masonry uses mud mixed with laterite and white lime, the strength is lower than M2.5, and the binding

capacity is very poor. Moreover, the connection between the vertical and horizontal walls is only built by interlocking, and there is no steel bar inside the wall (Figure 11). Therefore, the structural integrity and lateral resistance are poor. The connection between the gable and the roof truss is a purlin-on-wall flush-gabled roof. During the earthquake, the gable is easily destroyed and collapsed. The ash joint of the wall is also easy to crack under the action of the horizontal earthquake, which causes the wall to be damaged.

Due to the long history of construction, most of the walls of stone-wood structure houses have slight corrosion and crushing, and some walls have slight cracks, as shown in Figure 12.

In previous earthquakes, the destruction of stone-wood structure houses in relatively high-intensity areas is very serious. Taking the Wenchuan M8.0 earthquake in 2008 as an example, the field investigation results of the Earthquake Administration of Yunnan Province show that the stone-wood structure has slight cracks in the wall in the VI-degree area, and the wall cracks obviously or even partially collapsed in severe cases. In the VII-degree area, the stone-wood structure wall cracks obviously, the gable partially collapses, and the roof partially collapses; in severe cases, large cracks appear in the wall, the local wall tilts, the whole wall collapses, or all walls collapse. The stone-wood structure in the VIII-degree area has the phenomenon of an overall collapse of the house [7].

Fig. 12. The plastering layer on the outer wall of the stone-wood structure peels off

Fig. 13. brick-stone mixed structure in Hainan Province

Fig. 14. Brick-wood structure in Hainan Province (cavity wall)

3.2 Rural Houses Built Between 1990 and 2000

3.2.1 Architectural Features.

With the emergence and promotion of sintered clay bricks, the rural houses built between 1990 and 2000 began to use sintered bricks as masonry materials. Common structural forms include brick-stone mixed structures and brick-wood structures. The walls of these two types of structures were made of sintered clay bricks or volcanic rocks and bricks, and the beams and roof trusses were also made of wood. These two types of buildings are mainly distributed in rural areas of Hainan Province; old towns are also distributed, but some are no longer used. The brick-stone mixed structure and the brick-wood structure built in this period were almost single-layer, and the building facade form was the same as the aforementioned stone-wood structure.

The masonry materials of brick-stone mixed structures are volcanic stone and sintered clay brick (Figure 13). The modulus of volcanic stone is similar to that of ordinary sintered brick used in recent years, about 240 mm × 120 mm × 60 mm. Often in the lower part of the wall, volcanic stone is the masonry material, and the upper part of the wall uses sintered clay brick as masonry material. Because the gable does not open the window, so the gable is only close to the top of a small part of the use of brick masonry; the longitudinal wall is generally provided with 2 to 4 windows, and the window opening position is located on the brick wall. The window width is 0.5 m and the height is 0.8 m. The depth of the house is about 3m, and the width of the room is from 4m to 10m. Some houses open two doors on the longitudinal wall. The roof is a double-slope roof, and the roof structure is a purlin-on-wall flush-gabled roof. Roof materials use Chinese style tile.

The brick-wood structure is made of sintered clay bricks. The common wall thickness is 180 mm, and there are also cavity walls, as shown in Figure 14. The brick-wood structure also has no windows on its gable wall. There are generally 2 ~ 3 windows on the longitudinal wall, with a window width of 0.5 m and a height of 0.6 m. The roof is a double-slope roof, and the roof structure is a purlin-on-wall flush-gabled roof. Roof materials use Chinese style tile, which is similar to the aforementioned stone and wood structure.

3.2.2 Structural Features.

The roof forms of brick-stone mixed structures and brick-wood structures in Hainan Province are almost all purlin-on-wall flush-gabled roofs, so they are mainly supported by the transverse wall of brick or brick-stone mixed masonry; the roof truss is a wooden roof truss, and the wooden beam is used as a horizontal bearing member. The brick-stone mixed structure was built earlier, so the mortar used in the masonry is mud mixed with red clay and white lime, and the strength of the mortar is lower than M2.5. The mortar used in brick-wood structures is cement mortar, and the strength of this mortar is higher than that of mud. The vertical and horizontal walls of these two types of structures use interlocking masonry as the connection method, and there is no ring beam or constructional column (Figure 15). The foundation is a brick strip foundation made of brick.

3.2.3 Seismic Weak Links.

The brick-stone mixed structure and brick-wood structure built in Hainan Province from 1990 to 2000 are almost single-layer structures, without ring beams and constructional columns, and the integrity of the house is poor. The connection between the vertical and horizontal walls is built by interlocking, and there is no steel bar connection, so the structural integrity and lateral force resistance are poor. The connection between the gable and the roof truss is a purlin-on-wall flush-gabled roof, so the gable will be easily destroyed and then collapse during the earthquake. In the 7.0-magnitude earthquake in Lushan, Sichuan, the destruction of brick and wood structures is mostly due to the destruction or the flash of the gable, which leads to the collapse of the wooden roof [8].There are slight corrosion and crisp phenomena in the walls of some brick-stone mixed structures.

In addition, because the mortar of the brick-stone mixed structure is mixed with red clay and white lime, the strength is low, and it is easy to cause the wall mortar joint to crack under the action of the horizontal earthquake so that the wall is destroyed. The lower wall of the brick-stone mixed structure is stone masonry, and the upper wall is sintered clay brick masonry. The wall has stiffness change at the junction of the two materials. The lack of effective pull-up and low-strength mud will cause the wall to be damaged when subjected to horizontal seismic forces. Taking the Zhangxian M6.6 earthquake in Minxian County, Gansu Province on July 22, 2013 as an example, in the VIII-degree area of the earthquake, the cracks in the wall of the brick and wood structure are developed, and the penetrating and X-type cracks appear in the walls of a few houses, which are seriously damaged [9].

Fig. 15. interlocking masonry of the brick-stone mixed structure

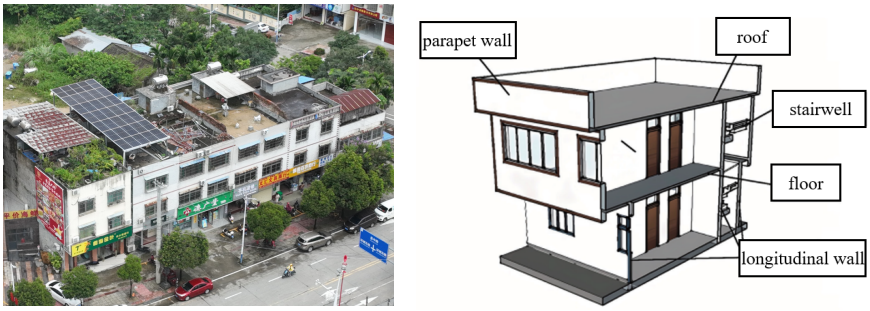

Fig. 16. Brick-concrete structure and its structural schematic diagram in Hainan Province

3.3 Rural Houses Built Between 2000 and 2010

3.3.1 Architectural Features.

Most of the rural houses built in Hainan Province from 2000 to 2010 are brick-concrete structures (Figure 16). The wall is made of sintered clay bricks, and the beams, slabs and columns are made of reinforced concrete materials. Such buildings have a huge stock in Hainan Province and are distributed in urban and rural areas. The number of floors of the building is mostly 2 ~ 3 layers, the building plane is mostly rectangular, and there are also irregular layouts. The building facades are also mostly rectangular, and some buildings have two floors over a layer of cantilever. The depth is mostly 6m, and the opening is 10m.

The masonry material of the brick-concrete structure is ordinary sintered red brick. The thickness of the load-bearing wall is 240 mm, and the thickness of the non-load-bearing wall is different. There are 240 mm, 180 mm, etc., some of which are only used to divide the space. The thickness of the wall is 120 mm. Because most of them are self-built by residents, to meet the needs of use, this kind of structure has a large bay, a large number of windows, and a large number of windows. There are two windows on each floor, with a window width of 1.2 m and a window height of 1.5 m. The roof materials and floor materials of such houses are almost cast-in-place concrete. Through investigation, it is found that there is almost no floor or roof made of precast slab in

Hainan rural houses. The roof type is a flat roof, and almost all the top floors have a parapet wall and an out-of-roof staircase.

3.3.2 Structural Features.

The brick-concrete structure is laterally supported by concrete beams and floors, and the brick masonry wall is used as a vertical load-bearing structure. According to the different construction times and the difference of government-led policies in different regions, the brick-concrete structure is divided into two types: construction measures and non-construction measures.

Most of the brick-concrete structures in Hainan Province adopt the mixed load-bearing of vertical and horizontal walls. The vertical and horizontal walls are generally connected with steel bars, and the integrity is good. The mortar is cement mortar, which has high strength. Most of these buildings consider the ring beam and constructional column in the design, and the floor is mostly cast-in-place, which has a certain seismic capacity. The foundation adopts the strip foundation.

3.3.3 Seismic Weak Links.

After 2000, most of the brick-concrete structures built in the township areas of Hainan Province were set up with constructional columns and ring beams. Most of the transverse walls and longitudinal walls were connected by steel bars, and the mortar strength was good, which met the requirements of the current seismic code and had a certain seismic capacity. However, compared with the urban area, the houses in the township area are mostly self-built, the number of windows is large and the size of windows is large, and there are irregularities in the plane and elevation, which does not fully meet the specifications, weakens the lateral force resistance of the wall, and makes the seismic capacity of the house decrease. In the survey area, a cantilevered balcony was found on the second floor of a masonry structure under construction. As shown in Figure 17, The cantilevered part is about 1m beyond the facade of the building. When the size and structural connection of the cantilever member do not meet the requirements of the specification, inclined cracks are likely to occur and develop at the end wall of the cantilever beam, resulting in overturning failure.

Taking the Lushan M7.0 earthquake as an example, for the structure without columns but with a two-layer cantilever, the stiffness of the upper and lower layers changes obviously. The mass of the second layer is large and the cantilever causes the whole structure to lean forward obviously, which is seriously damaged in the earthquake , as shown in Figure.18 [8].

In some buildings, the parapet wall and the out-of-roof staircase are not provided with tie bars. In the event of an earthquake, the out-of-roof components are easily damaged or even collapsed by the whipping effect. Generally, in the VI-degree area, the multi-story brick-concrete structure begins to appear with partial cracking of the parapet wall; and the cracking phenomenon is more serious in the VII-degree area; in the VIII-degree area, the parapet wall and the upper part of the wall are seriously cracked or broken; in the IX-degree area, the mountain tip wall and the parapet wall generally collapsed [10].

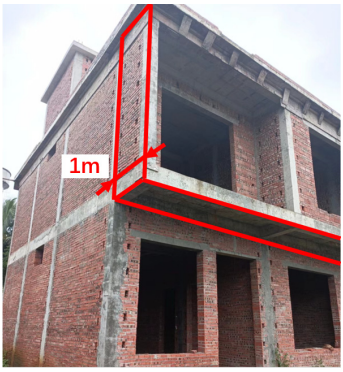

Fig. 17. A brick-concrete structure under construction in a township of Hainan Province has a cantilevered part on its second floor

Fig. 18. A two-story cantilevered brick-concrete structure was damaged in Lushan earthquake.

Fig. 19. A framework structure under construction in Hainan Province

3.4 Rural Houses Built After 2010

3.4.1 Architectural Features.

With the development of the economic level, frame structure houses gradually appeared in township areas of Hainan Province after 2010. The frame structure houses use reinforced concrete materials as beams, columns and plates, and the filled walls are made of ordinary sintered bricks. Such buildings are mainly distributed in urban areas of Hainan Province (Figure 19). In recent years, there have been many new repairs in rural areas. The area of frame structure type houses in Hainan Province accounts for about 70.6 %, and the number is relatively large. The frame structures in the township areas of Hainan Province are mostly 2-3-storey self-built houses, and there are also single-storey buildings. In addition, the frame structure buildings in most townships and towns retain and rust-proof the exposed column steel bars on the top floor, so that the residents can cover the floors when they are richer in the future.

The building plane of the frame structure is mostly rectangular, and there are also squares. The building facade is also rectangular or square, and the roof type is a flat roof. The thickness of the filling wall of the house is generally 240 mm, and there are also 180 mm. The number of frame spans is mostly 2 to 3.

The building plane of the frame structure is mostly rectangular, and there are also squares. The building facade is also rectangular or square, and the roof type is a flat roof. The thickness of the filling wall of the house is generally 240 mm, and there are also 180 mm. The number of frame spans is mostly 2 to 3.

3.4.2 Structural Features.

The frame structure is composed of concrete beams and columns to bear all the load of the house. The frame is often used as the load-bearing structure, and the infilled wall only plays the role of enclosure and separation.

This kind of frame structure is mostly built by residents themselves or collectively. The foundation adopts a strip foundation, and the frame form is almost two or more spans. Ordinary bricks are used as infilled walls, and there are tie bars between infilled walls and columns. However, because most of them are self-built, the arrangement of reinforcement between infilled walls and columns and the symmetrical form of frame columns are more casual. Many buildings have the situation of canceling the frame column with a deep beam for the large opening of the bottom layer, and there are also cases of strong beams and weak columns, which do not fully meet the code.

In the towns with more developed coastal tourism economy, some village residents adopt the method of outsourcing to the construction team. The frame structure built by the construction team has mostly an independent footing. The layout of the reinforcement between the infilled wall and the column and the symmetrical form of the frame column are more in line with the specifications. The construction quality is good, the building has constructional measures and good seismic capacity.

3.4.3 Seismic Weak Links.

The frame structures built in the township areas of Hainan Province after 2010 generally have constructional measures and have certain seismic behavior. Some of the houses built by the construction team have good construction quality, sufficient constructional measures and good seismic behavior. However, due to the fact that most of the frame structures are self-built by residents, the connection between the frame columns and the infilled walls is not sufficient (Figure 20), and there are large bays and stairwells at the end or corner of the house, resulting in the uneven layout of the plane stiffness of the house, which is prone to cracks or even collapse of the infilled wall and torsion of the plane of the house during the earthquake.

Due to commercial use or other reasons, the bottom layer of the frame structure facing the street in some township areas adopts a large bay and depth, and even removes the frame column in the middle of the bottom layer and adopts the deep beam to transmit the load (Figure 21). This causes the longitudinal deep beam to easily collide with the cross beam during the earthquake and causes the cross beam to be destroyed.

Most frame structures consider seismic fortification in the design and construction, so the frame structure houses built according to the code have better seismic performance. Taking the Lushan 7.0 earthquake as an example, in the area of VIII degree and above, the serious damage of the frame structure is only about 5% [8]. However, in the field investigation, it is still found that there are some residents ' self-built frame structure houses under construction, and the number of tie bars reserved for the frame columns does not conform to the specification. In the Lushan earthquake, the failure of masonry-infilled walls of frame structures is still common. The reason is that the local collapse or cracking occurs due to the weak connection between the infilled walls and the beams and columns.

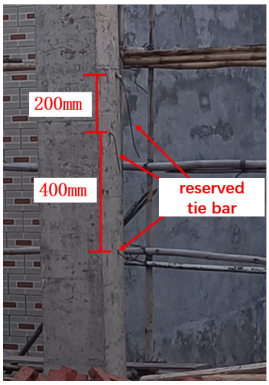

Fig. 20. The number and distance of tie steel bars reserved in frame columns are inconsistent with the code

Fig. 21. A frame structure under construction replaces the bottom middle frame column with a deep beam

4 CONCLUSIONS AND SUGGESTIONS

Through a detailed sampling survey of rural houses in township areas of Hainan Province, this paper analyzes the proportion, construction features, seismic performance, and seismic weaknesses of various structural types of houses. The conclusions and recommendations are as follows :

- The houses in the township areas of Hainan Province are mostly masonry structures, and there are many old masonry structures. The masonry materials of this type of structure are mostly mixed with stone and brick or just stone, and they do not have construction measures. The seismic behavior of this kind of building is poor, and it is very vulnerable to damage when encountering local fortification-intensity earthquakes. The local government can give full play to its functions in the rural revitalization strategy, adopt specific preferential policies, and publicize and encourage villagers to build new houses with seismic construction measures.
- Since there have been no major earthquakes in Hainan Province in recent years, the public's awareness of earthquake resistance and disaster prevention is generally weak. Some self-built brick-concrete structures and frame structures have not been fully designed and constructed according to the requirements of the code, and there are widespread practices such as canceling frame columns for large bays, irregular plane facades, strong beams and weak columns, which are unfavorable to the seismic behavior of the structure. The previous earthquake damage shows that the brick-concrete structure houses and frame structure houses that are not strictly designed and constructed in accordance with the specifications almost all have earthquake damage under high intensity, and even serious and above damage will occur under high intensity. The government should strengthen the propaganda of disaster prevention and mitigation knowledge, improve the people's awareness of earthquake resistance, and strengthen the supervision of new buildings' design and construction quality.

- Under the action of large magnitude earthquakes, the seismic capacity of frame structure is generally higher than that of masonry structure, which has good integrity and seismic performance. In areas where conditions permit, housing in the form of frame structures can be promoted through policy and publicity.

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