Wood as the Principle: Research on the flexible Standardization of Traditional Large-Scale Wooden Residential Structures in Chinese Tubao

Yuyu Zhang [1], Xintong Zhu [2] , Liang Zhang [3]

ABSTRACT: This paper focuses on the flexible standardized construction of traditional Chinese large-scale timber residential structures, selecting three typical cases from central Fujian in the 19th century: "DafuZhen," "GuangyuBao," and "RuiqingBao." From the perspective of deconstructing craftsmanship, it excavates and deduces the technological information embedded in the existing material remains, summarizing construction strategies under multiple objective constraints. It explores how ancient craftsmen employed modular and flexible standard design strategies, as well as their innovative paths of passive adaptation and active technological improvement. This study proposes a method for understanding and interpreting the construction techniques of Tubao buildings, providing references for historical building preservation and modern modular housing design. It emphasizes integrating traditional wisdom into contemporary practices to promote sustainable architectural development.

KEYWORDS: Tubao, timber structure, flexible standardization, traditional Chinese construction

1 – INTRODUCTION

When exploring large-scale residential Projects that accommodate mass populations, it is necessary to revisit the modernization transformation of architecture in the 1920s: the Bauhaus School, represented by Walter Gropius, introduced the concept of "standardized" housing under an industrial production system[1] . This fundamentally restructured the efficiency logic of construction and the mode of social production[2] , making a significant contribution to the modernization of architectural design.

China's traditional folk construction system has long maintained a practice with "standard" significance. The official establishment of such "standards" can be traced back to the Song Dynasty (960-1127) with the Yingzao Fashi (Construction Standards) and the Qing Dynasty (1616-1912) with the Gongcheng Zuofa (Engineering Practices). These engineering classics aimed to comprehensively control the scale hierarchy, material usage, and construction timelines of buildings through defining different sizes of wooden component cross-sections as Control Modulus units, assigning hierarchical meanings to them, and organizing other components' dimensions and methods accordingly. Thus, establishing that traditional Chinese timber-frame construction was a modular and flexible Standardization design and building system.

Modern industrial production models are characterized by mechanical and prefabricated "standardization," but they impose numerous constraints when addressing unconventional construction conditions. In contrast, ancient Chinese construction systems demonstrate significant adaptability. Hence, how did craftsmen achieve flexible construction of large-scale timber buildings in complex terrains while adhering to the goal of "standardization"?

2 – CONTEXT: MULTI-OBJECTIVE DRIVEN CONSTRUCTION STRATEGIES

As a typical representative of large-scale mountain residential architecture in central Fujian, the Tubao need to simultaneously satisfy living, ceremonial, storage, drainage, and defense functions for over a hundred family members. For the building site, initial minor modifications are made based on the natural state of terraced hillsides. Following this, an array layout is formed starting from the central axis, including Central courtyard, longhouses, and gutters, with Over-canal roofed bridges facilitating lateral traffic across gutters. Regarding the enclosing structure, a closed defensive system is constructed through high rammed earth walls, integrating facilities such as watch towers, defensive corridors, and loopholes[3] (Figure 1).

Therefore, the construction techniques of Tubao, driven by multiple objectives, exhibit notable regional characteristics: to address the organization of large-scale Frame structures, timber frame structures rely on modular design and flexible Standardization production logic, which also influences the graded planning of stone foundations and the construction methods of rammed earth walls. This constitutes the core construction logic distinguishing Tubao from flatland residences.

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Figure 1.Construction Environment and Characteristics of Tubao

1, 2, 3: RuiQingBao, GuangYuBao, and DaFuZhen located in hilly terrain environments.4: Ceremonial space (main hall) on the central axis of GuangYuBao.5: Central courtyard construction on the central axis of GuangYuBao (viewing from the defensive corridor towards the south).6, 7: Curved slope defensive corridors on GuangYuBao.

This study selects three typical cases from central Fujian in the 19th century: "DaFuZhen", "GuangYuBao", and "RuiQingBao", attempting to summarize the construction strategies under multiple objective constraints. It should be noted that although the construction process cannot be reproduced, the embedded construction techniques still retain their vitality. Thus, this research, from the perspective of deconstructing craftsmen's skills, excavates and interprets the existing material remains' craft information, proposing a method for understanding and interpreting the construction techniques of Tubao architecture.

3 – ORGANIZATION: MULTI-TRADE TECHNICAL COLLABORATION MECHANISM

Traditional construction is characterized by the collaborative work of multiple trades. In the construction of composite structures and functional buildings such as Tubao, there are three core technical entities—geomancers, carpenters, and stonemasons—whose collaboration harmonizes cultural and material factors, presenting a pathway for transforming ecological concepts and spatial order into construction technical parameters.

3.1 GEOMANCERS: PLANNING THE IDEAL FENG SHUI MODEL

The geomancer's role is to focus on the owner's birth-related destiny (the five-element attributes and directions corresponding to their birth date), integrate the family's living and development needs, evaluate the environmental characteristics of the site, and seek an ideal Feng Shui model that maximizes benefits while avoiding harm. This establishes a spatiotemporal connection between the building and the generational fate of the family members.

In the construction practices of central Fujian Tubao, geomancers adhered to the classic residential layout of "backing onto mountains and facing water." Meanwhile, they adapted to diverse hilly terrains, controlling the building's orientation, the elevation of the site's front and rear points, and refining the main axis orientation and gate direction into specific angles tailored to the owner's destiny. In complex mountainous environments, this effectively organized living spaces that embody life aspirations, thereby encouraging the owner's investment in such large-scale buildings and laying the foundation for Tubao construction.

3.2 CARPENTERS: PARAMETER CONVERSION AND TECHNICAL COORDINATION

Each technical entity has its systematic design methods, but only carpenters can convert abstract Feng Shui indicators such as orientation and dimensions into concrete spatial coordinates, component sizes, and design parameters. They then transmit these parameters to other trades, coordinating the structural relationships between timber frames, stone foundations, and rammed earth walls. This achieves control over the building's layout and the hierarchical organization of its structural system. As a result, carpenters occupy a central position in the technical coordination of the team, overseeing the entire process from planning and design to construction.

3.3 STONEMASONS: SUPPORT AND CONSTRAINTS FOR TIMBER STRUCTURES

The stonemason's primary task is to make minor modifications to the hilly terrain to create a building foundation compatible with the timber frame modulus. Under the guidance of the carpenter's planning and geological assessments, they complete site leveling, terrace grading, slope shaping, and excavation of gutters. Pre-Embedded Cantilever Stones are installed on the gutter sidewalls to provide foundational support points for the upper Over-canal roofed bridges. In mountainous construction, dynamic deviations often arise between the carpenter's planning and the actual foundation construction status (Section 5.2). Therefore, stonemasons must adjust the size, positioning, and construction methods of stones on-site within the allowable range of the carpenter's plan to reconstruct the reference plane for timber structure installation. This forms a bidirectional constraint relationship based on standard timber frames and feedback from foundation construction adjustments (Figure 2).

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Figure 2. Representation of the Coordination Between Carpentry and Stonework in Tubao

The aforementioned collaboration mechanism can be summarized as follows: with carpenters as the technical coordinators, cultural concepts and the owner's requirements are transformed into spatial structure parameters and ultimately realized through construction activities as living spaces. This cultural and technical symbiosis is concretely embodied in the spatial and structural organization of Tubao (Figure 3): the Central courtyard along the central axis adopts a multi-courtyard layout; the longhouses are arranged in repetitive east-west strips, with their number depending on site conditions and the craftsmen's design capabilities. The cultural essence of Tubao originates from the traditional courtyard style brought by the southward migration of the Han people from the Central Plains, symbolizing traditional rites, combined with pragmatic thinking shaped by the needs of family habitation and defense in mountainous environments[4] .

4 – GOVERNING STANDARDS FOR MAIN STRUCTURAL DESIGN

4.1 "CONTROL MODULUS" OF THE FRAME AND PROTOTYPE DERIVATION MECHANISM

Each spatial attribute in Tubao corresponds to a specific frame typology. When carpenters design frames, they often use a "prototype" as a reference and derive multiple configurations through systematic rules. How is such a "prototype" determined within the large-scale structural organization of Tubao?

From Figure 3, it can be seen that the Central courtyard serves as the core unit for ceremonial activities. The spatial hierarchy along the central axis is differentiated by various frame types, while the inward-facing nature of the courtyard causes similar frames to exhibit asymmetry along the front-rear axis[5] . In contrast, the longhouses, which serve purely residential functions, require their structural systems to maintain relative stability during the mass processing of components and repetitive arrangement of units. This ensures uniform stiffness distribution across frame assemblies on different elevation bases, making their modular and standardized characteristics more pronounced.

Thus, it can be inferred that craftsmen prioritize establishing a "control modulus" for the frequently used longhouse frame as the "prototype." They then adjust the scale by adding or reducing "Bu" (the distance between adjacent purlin centers) to derive other configurations from the "prototype." As a result, all frames in actual cases—regardless of rank, function, or base conditions—are adjusted based on the same modular principle[6] .

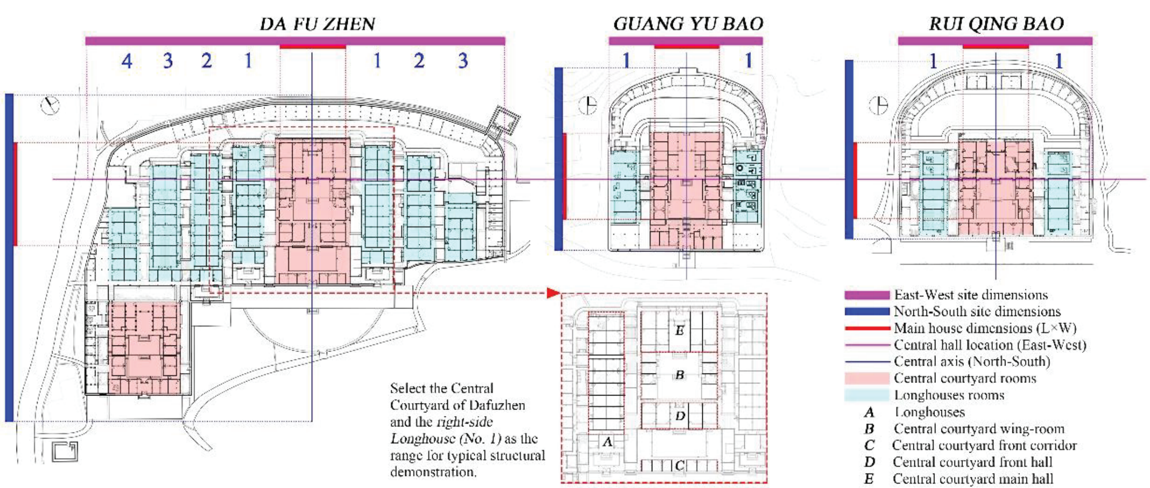

Figure 3. Diagram of Spatial Organization in Three Tubao Cases

Table 1. Mean Values of Five Frame Specifications in "DaFuZhen" (Unit: mm)

Project	Central column height	Bu number	Control modulus 1	Control modulus 2	Core unit modulus	Corridor Bu
A	5110	10	830	830	3320	1030
B	3941	6	763	747	3020	1150
C	3454	5	685	650	2670	817
D	4370	10	758	762	3040	1170
E	5173	12	915	915	3660	1100

4.2 CORE UNITS AND EXPANSION METHODS OF TYPICAL FRAMES

4.2.1 Core Unit

From the "DaFuZhen" case (Figure 3), five recurring Tubao frame specifications can be summarized (Figure 4,Table 1). Their structural performance shares a commonality: all are based on the "four-Bu three-column" system as the core unit. Symmetrical about the central column, each side is supported by one ground column and one short column, with tie-beams connecting them to form a stable force-transfer system. In this core structural unit, the total span of four "Bu" constitutes its dimensional benchmark. Measured data show that the core unit spans of the five frame types range from 2670-3660mm, with the longhouse frame A (3320mm) slightly larger than the median value (3142mm). This benchmark reflects that the length-to-span ratio of horizontal wooden poles falls between 1:16 and 1:13, facilitating rapid modular expansion of longhouse units while maintaining comfortable living dimensions. Other frame specifications also use the "four-Bu three-column" core unit as a reference, adjusting Bu values and column heights to maintain configuration patterns and ensure continuity in load transfer paths.

4.2.2 Expansion Methods

Based on the core units of each frame specification, expansions are made symmetrically to both sides according to the spatial usage attributes, completing the overall configuration. Longhouse frame A serves as the "prototype," and due to the equalized demands of daily living, it expands two Bu on each side (totaling eight Bu), forming two symmetrical compartments without decorative beam structures. Auxiliary wing-room frame B maintains the "prototype" configuration due to its single function and smaller scale. Frames C, D, and E along the Central courtyard axis differ in spatial hierarchy, with their front slopes extending 0, 1, and 3 Bu respectively. Non-symmetrical roof slopes, bracket sets, and carved beams emphasize the spatial hierarchy, while the rear slope features simple support structures to reinforce the ceremonial sequence of the central axis. This derivation mechanism of the "prototype" is achieved by incrementally prefabricating columns, purlins, and tie-beams, reflecting a design logic that progresses from parts to the whole while balancing functionality, stability, and order.

Notably, although the corridor Bu and cantilevered dimensions of various frames slightly exceed the control modulus, their numerical changes remain positively correlated with Bu, reflecting the craftsmen's response to saving ground space and meeting traffic requirements. Additionally, special frames such as study pavilions, privy and woodsheds, and longhouse courtyards, though appearing only in localized spaces, are all governed by this modular system[7] .

4.3 CORRELATION BETWEEN STONE FOUNDATIONS AND TIMBER FRAMES

The advantage of applying standardized, modular timber frames in hilly areas lies in achieving precise control and adaptive adjustments for irregular building foundations through unified dimensional units. This is specifically reflected in three aspects: height difference decomposition, site planning, and gutter handling (Figure 5).

4.3.1 Height Difference Decomposition and Level Adjustment

After geomancers determine the front and rear elevations of the site, carpenters decompose the total height difference into terraced levels and step differences suitable for stonemason construction based on frame modulus. For example, in "DaFuZhen," a nearly 6000-square-meter site with a front-to-rear height difference of 3.5m is longitudinally divided into 3-5 levels, with each level ranging from 330-900mm. Level design considers two points: first, ergonomic requirements ensure that stonemasons can divide each Bu into 2-4 stairs, each 150-200mm high; second, it satisfies the ceremonial sequence of the central axis by adjusting terrace height differences to enhance spatial hierarchy. For instance, the height difference between the 4th and 5th terraces of the Central courtyard reaches 800mm, while the 1st and 2nd terraces of the longhouse front yard differ by only 480mm, reflecting the need to elevate the floor of the main hall area to enhance dignity. This hierarchical logic is also evident in sloped defensive corridor foundation planning (Section 5.3.1), corroborating the guiding role of the modular system in tiered strategies.

4.3.2 Modular Control of Site Layout

When carpenters plan the site layout using modular thinking, they do not rely on grid-based compositions but instead adopt a logic better suited to sloping terrain: using the central hall axis as a reference, the starting points of adjacent longhouse foundations retreat outward by 2m sequentially, forming multiple closed contour lines through stepped offsets (Figure 5). The dimensions of each foundation row are controlled by standardized frame modulus and grouping rules. Taking the longhouse frame A in "DaFuZhen" as an example, its core unit extends two Bus on both sides to define room depth, and its overall dimensions limit the width of the longhouse foundation. The lateral corridor Bu modulus constrains the dimensions of circulation spaces, and the allowable number of rooms is determined based on site conditions, with bay

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dimensions limited by the effective span of tie-beams between frames. This approach generates the Tubao's site layout and foundation dimensions.

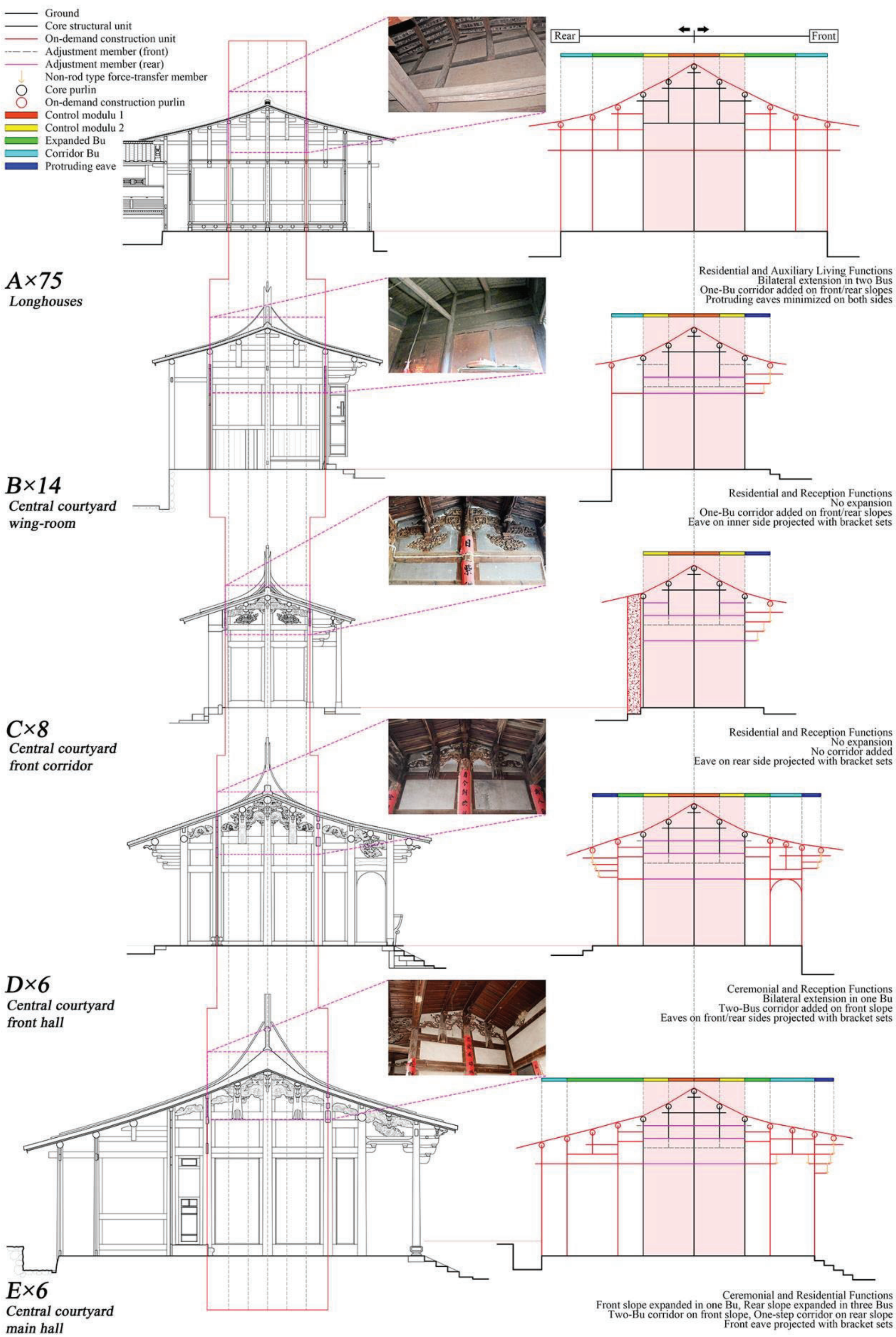

Figure 4. Prototype and Alteration of DaFuZhen Frames

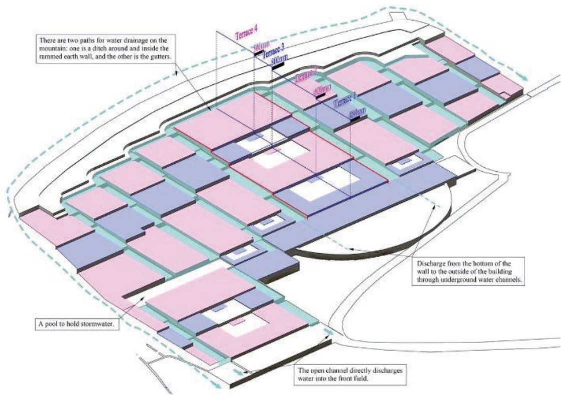

Figure 5. Height Difference Decomposition, Site Planning, and Gutter Handling in DaFuZhen

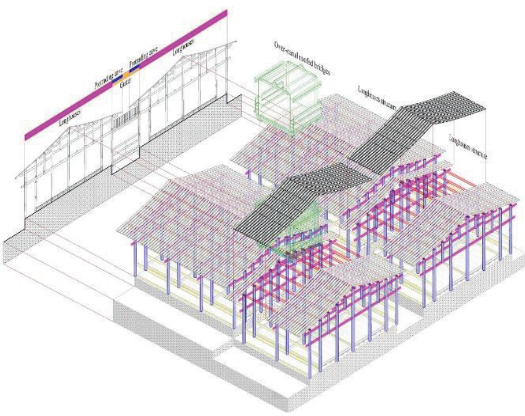

Figure 6. Correlation Between gutter and Timber Frame Modulus

Table 2. Proportional Relationship Between Gutter Base Width and Longhouse Frame Eave Projection in "DaFuZhen" (Unit: mm)

Longhouse Framework	*Protruding Eave Projection*	*Gutter Width*	*Double-Bay Intercolumniation*	*Longhouse Foundation Width*	*Longhouse : Gutter : Protruding Eave Ratio*
A01	963	2564	2870	8886	28:8:3≈9:3:1
A02	963	2564	2870	8886	28:8:3≈9:3:1
A03	1000	2668	2870	8737	24:8:3≈8:3:1
A04	1000	2668	2870	8720	24:8:3≈8:3:1

4.3.3 Correlation Between Gutters and Timber Frame Modulus

The design strategy for gutters relates to the rainy climate of central Fujian. As a special component of foundational engineering, the width and excavation depth of gutters are often determined by stonemasons' experience. No direct frame installation occurs above the stone foundation surface; instead, Pre-Embedded Cantilever Stones are installed on the sidewalls to support Over-canal roofed bridges. As shown in Table 2, the width of the longhouse foundation, the lateral width of the gutter (or intercolumniation on both sides of the channel), and the overhanging eave dimension of longhouse frame A roughly follow a 9:3:1 ratio, exhibiting a threefold relationship. Although this ratio reduces light exposure by at least 60% due to the overlapping eaves, it maximizes ventilation and flood drainage efficiency. The average width and depth of the gutter (800mm) are coordinated with the height of the Over-canal roofed bridge, protecting the timber structure from water erosion during drainage. While gutter dimensions do not directly adopt frame modulus, their planning method remains influenced by it, reflecting a modular logic governing timber structures from parts to the whole, thus constituting the uniqueness of Tubao construction (Figure 6).

5 – FLEXIBLE STANDARDIZATION FOR ALTERATION DESIGN

5.1 CONTROL ANCHORS OF THE FRAME AND DYNAMIC DESIGN MECHANISM

In Tubao construction, complex foundation conditions necessitate dynamic design adjustments for Over-canal roofed bridges and defensive corridor frames based on site construction conditions. To achieve adaptive construction goals, craftsmen ensure the rational assembly of the overall structure by precisely controlling key structural "anchor points." Based on this, the discussion of two special construction areas—Over-canal roofed bridges and defensive corridors—reveals how craftsmen establish a balance between local flexibility and overall structural stability.

5.2 CONSTRUCTION PROCESS DEDUCTION OF OVER-CANAL ROOFED BRIDGES

Over-canal roofed bridges serve as horizontal connectors between gutter bases on both sides while fulfilling composite functions such as transportation, living, and livestock management. The adaptive construction strategy includes six technical key points (Figure 7, Figure 8):

5.2.1 Site Planning: Determination of Traffic Nodes

The starting points of each row of longhouse foundations in Tubao are typically arranged in a stepped layout. Craftsmen use longhouse frameworks as a reference to position the Over-canal roofed bridge timber structures at the ends of each level base. The horizontal connection characteristics enhance the lateral stiffness of the main buildings on both sides.

5.2.2 Structural Positioning: Handling of PreEmbedded Cantilever Stones

After determining the timber frame's planar positioning, craftsmen must pre-embed four cantilever stones on the sidewalls of the gutter to support the upper timber structure. Survey data from DaFuZhen and GuangYuBao (Table 3, Table 4) show that the distance between the cantilever stones and the edge of the wooden floor is concentrated between 320-340mm (allowing ±10mm error), indicating that stonemasons' technical systems include construction redundancies to address errors in natural stone stacking. For accurate column alignment, cantilever stones must be

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precisely embedded at load concentration points. Existing misalignments between some cantilever stones and timber structures may result from later maintenance or functional adjustments.

5.2.3 Volume Design: Determination of Floor Span

The floor span is determined by the positions of the pre-embedded cantilever stones and matches the roof beam span (i.e., the distance between the front and rear eave purlins). Since Over-canal roofed bridges lack side passages and have minimal roof overhangs, whether the floor span needs extension depends on specific conditions. Coordination is required between the lower cantilever stone positioning, floor edges, upper beams, and adjacent main structures. Comparing the two cases (Table 3, Table 4), the average span of Over-canal roofed bridges in DaFuZhen is 2900mm, while in GuangYuBao, it is 2500mm. This suggests that craftsmen define Over-canal roofed bridges as living spaces rather than traffic corridors, using modular flexibility to accommodate different site conditions.

5.2.4 Height Anchor Points: Control of Roof Slope

The height of the Over-canal roofed bridge frame is controlled by the "Lift Ratio" (the vertical height-to-span ratio of the beam frame), described in "water" units. Once the beam span is determined, the frame height is effectively set by a standard roof slope. The average lift ratio of Over-canal roofed bridges in DaFuZhen is 3.4 water, significantly higher than the 2.5 water of main house frame D but close to the 3.5 water of longhouse frame A. Similar observations are found in GuangYuBao, reflecting craftsmen's trade-offs between structural hierarchy and drainage efficiency.

5.2.5 Stiffness Anchor Points: Selection of Column Borrowing

The ground columns of Over-canal roofed bridges correspond to one column position near the central axis of the main building. Depending on existing beam and purlin positions, the front and rear eave purlins are connected, and additional components are added to complete the force transmission system. To save materials and space, the Over-canal roofed bridge rigidly connects only on the side near the central axis, with flexible connections on the other side. However, two independent frame types exist in practice: (1) ceremonial spaces (e.g., longhouse front halls) require complete frames to enhance ritual significance; (2) Over-canal roofed bridges at the eastern and western boundaries, constructed last, are forced to be independent due to misalignment with the main structure. This "semi-dependent" mode balances functional use with material costs.

5.2.6 Configuration Methods: Adjustment of Frame Scale

The number of Bu in Over-canal roofed bridge frames follows the principle of balanced force transmission, typically corresponding to 2, 4, or 6-Bu modules of longhouse frames. Expansion schemes vary based on usage requirements: If adjusting the roof's front and rear eave heights, an additional Bu can extend the eave beyond the floor. If the borrowed column becomes a gold column (inner eave column), 1-2 additional ground columns are added at the edges for reinforcement. Frames with more than 2 Bu often use ground columns as pivot points to add 430mm-wide seats on one or both sides. This width matches the single-Bu span of Over-canal roofed bridges, indicating that both primary frames and auxiliary furniture are designed under the same modular system, ultimately achieving structural and functional adaptation.

The above analysis shows that the core adaptive strategy of Over-canal roofed bridge construction lies in the craftsmen's decision-making mechanism based on construction sequence, focusing on the structural essence of complete force transmission paths[8] . This approach demonstrates ingenuity in spatial and structural integration and lightweight design. Unlike the explicit modular constraints of general frames, this construction mindset forms an implicit structural concept through experience accumulated during dynamic construction—a topological adaptation system integrating modular benchmarks and geometric features.

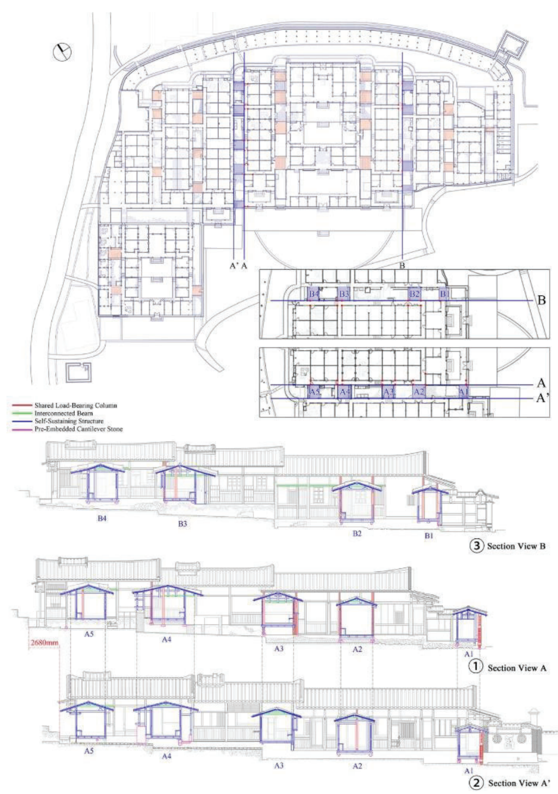

Figure 7. Schematic of Over-canal roofed bridge construction in DaFuZhen.

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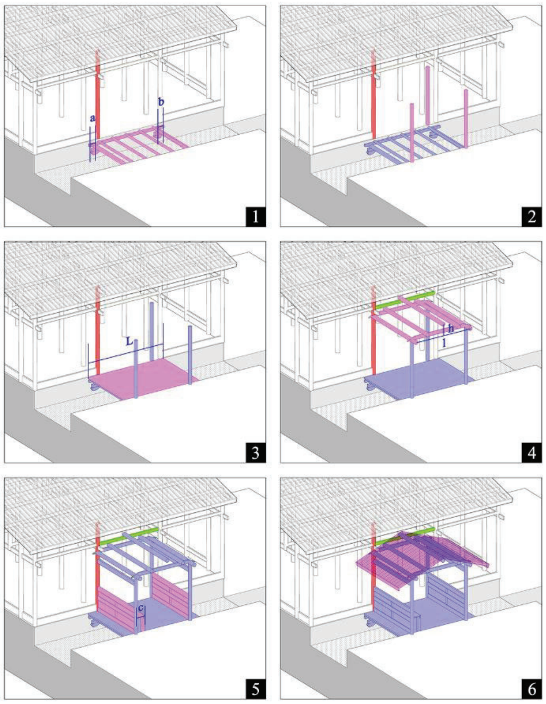

Figure 8. Construction process and technical key points of Over-canal roofed bridges

5.3 CONSTRUCTION PROCESS DEDUCTION OF DEFENSIVE CORRIDORS

Defensive corridors are crucial components of Tubao's defense system, forming multi-level continuous loop paths at the rear of the building on hilly slopes and curved planes. Their bases slope down from the central axis to both sides and are enclosed by rammed earth walls, meeting the family's tactical mobility needs for patrolling, lookout, and shooting, while housing ceremonial study pavilions at the central high point. Craftsmen face three main challenges: grading and turning of arc-shaped bases, control of the timber frame system's integrity and continuity, and joint details between rammed earth walls and timber frames[9] .

5.3.1 Base Grading: Non-uniform Step Treatment Technology

When designing base grading, carpenters follow the study pavilion elevation and arc turning angle parameters preset by geomancers, using a non-uniform step strategy to resolve vertical differences between defensive corridors and main building bases. This process involves two main steps (Figure 9): (1) Establishing Elevation Baselines: Based on the absolute height difference between the center point α of the study pavilion base and the end corner β of the main building base, along with plane dimensions and accessibility standards, calculate the number of steps and determine the starting point γ of the defensive corridor base. (2) Gradient Zoning Control: Using β as the base point, divide the core area and edge segments, determining non-uniform step segment points δ1, δ2: In the core area (between left and right endpoints α1, α2 and δ1, δ2), arrange 4 core steps with 120–150mm height differences on both sides. In the edge area (between δ1, δ2 and γ1, γ2), form several steps with 150mm-400mm height differences constrained by terrain curvature and width. As shown in the figure, the edge turning area of the defensive corridor in RuiQingBao is smaller than in GuangYuBao, with stair design following centripetal and even distribution rules, resulting in better overall structural stability.

Table 3. Measurement data related to Over-canal roofed bridges in DaFuZhen (Unit: mm)

Project	***floor span(L)***	***Pre-Embedded Cantilever Stone (North)(a)***	***Pre-Embedded Cantilever Stone (South)(b)***	***Purlin center distance between front & rear eaves(l)***	***Roof pitch height(h)***	***Hydraulic gradient value(l:h)***	***Seat beam clearance©***
Max	3856	1093	920	3678	650	5.5	510
Min	1888	50	0	1550	179	2.5	303
Most	3750	335	425	2530	308	2.7	440
Average	2912	347	288	2707	404	3.4	407
Hall	/	/	/	10800	2160	2.5	/
Longhouse	/	/	/	8571	1218	3.5	/

Table 4. Measurement data related to Over-canal roofed bridges in GuangYuBao (Unit: mm)

Project	***floor span(L)***	***Pre-Embedded Cantilever Stone (North)(a)***	***Pre-Embedded Cantilever Stone (South)(b)***	***Purlin center distance between front & rear eaves(l)***	***Roof pitch height(h)***	***Hydraulic gradient value(l:h)***	***Seat beam clearance©***
Max	4470	510	542	4365	748	3.5	457
Min	400	162	263	1089	333	1.6	275
Most	3385	162	263	4365	748	2.8	457
Average	2520	327	406	3240	566	2.8	393
Hall	/	/	/	13202	1923	3.4	/
Longhouse	/	/	/	8760	1465	3.0	/

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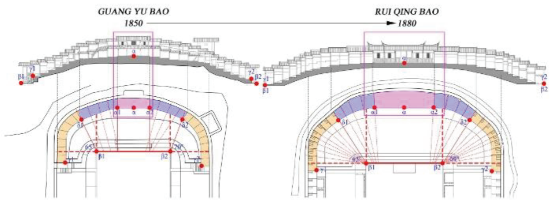

Figure 9. Comparison of base grading treatments in GuangYuBao and RuiQingBao.

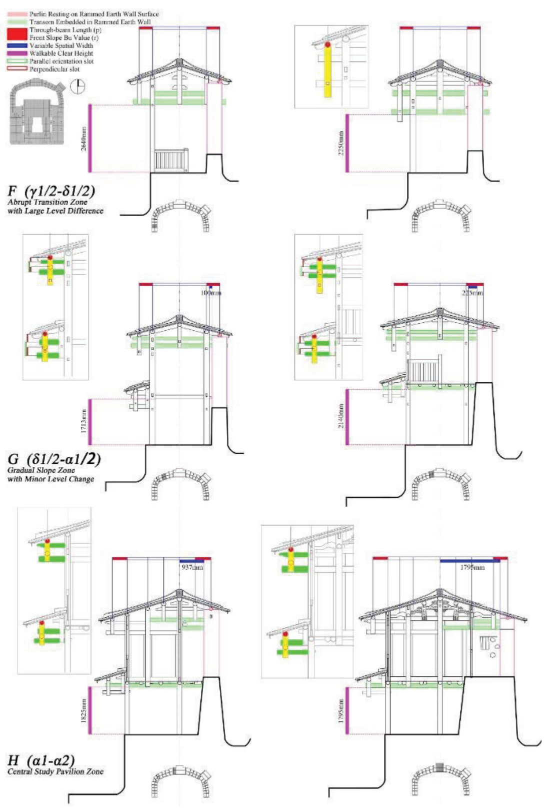

Figure 10. Joint control schematic of the defensive corridor in GuangYuBao

5.3.2 Frame Selection: Functional Adaptation Technology

Based on the different spatial functions of graded base zones, carpenters designed three types of timber frames for the defensive corridor in GuangYuBao (Figure 10). The on-demand configuration of these three frame types achieves structural transformation of Spatial Performance (Table 5), leaving room for flexible handling of joint details with rammed earth wall construction.

5.3.3 Joint Coordination: Balancing Construction Parameters and Flexible Space

Hilly bases limit the precision of arc-shaped stone foundations and their upper rammed earth walls, creating gaps between rammed earth walls and timber frames. To ensure the integrity of the defensive corridor frames and roof continuity across varying heights and angles, it is necessary to control the flexible space influenced by joint parameters, enabling rectangular timber frames to adapt to leap-level and turning bases. This process involves two key technical points (Figure 10): (1) Stability Between Frames: Solving the problem of synchronized control of front, back, up, and down forces on frames across different heights and angles requires joint coordination. Key measures include ensuring the distance between two parallel orientation slots on a column is controlled within 250-400mm, with a height difference of at least 150mm for perpendicular slots. From the overall frame perspective, these measures also ensure Walkable Clear Height for unobstructed passage between floors, controlled within 1.7m-2.7m. (2) Relationship Between Frames and Rear Walls: To achieve roof continuity of defensive corridor frames under complex base conditions and rammed earth wall constraints, all rear slopes adopt a dual-parameter strategy to control the gap between timber frames and curved rammed earth walls. In sharp-turning sections (γ-δ), the length of tie-beams p continuously increases, maintaining the distance q between rear slope purlins (positioned on the rammed earth wall surface and the golden purlin) consistent with the front slope Bu value r. This controls flexible space between timber frames and rammed earth walls within 0-1800mm (4-Bu modulus of frame H), resulting in a continuous turning feature of the ridge line.

The core adaptive strategy of defensive corridor frames lies in combining geometric and numerical control anchor points to enhance the adaptability of rectangular frames to curved bases and reinforce joint stability. Such special constructions reflect craftsmen's superior performance in responding to original ecological construction environments through micro-modifications on seemingly heterogeneous bases. Technologically, we observe that the same group of craftsmen used primitive adaptive strategies in constructing the defensive corridor in GuangYuBao, while their practices 30 years later in RuiQingBao demonstrate technological iteration.

Table 5. Three types of timber frame configurations and spatial efficiency in the defensive corridor of GuangYuBao

Functional partitioning	***Frame Typology***	***Construction Characteristics***	***Spatial Performance***
Abrupt Transition Zone with Large Level Difference (γ-δ)	F-1-column-4-Bu system	Short columns with penetrating tie-beams interlocked with rammed earth	Ensure 2070mm emergency access corridor [9]
Gradual Slope Zone with Minor Level Change (δ-α)	G-2-column-4-Bu system	Continuous columns detached from rammed earth wall; added tie-beams reserved for installation nodes of front cantilevered eaves and second-floor platform	Create 2230mm double-height space
Central Study Pavilion Zone (α1-α2)	H-Subtype of D	Inherit the ceremonial configuration of the main hall's forecourt	Maximum clear span 3115mm enhances the ceremonial hierarchy of the central axis

6 – CONCLUSION

From the design and construction inference process of three Tubao buildings, it can be seen that craftsmen faced complex construction sites, large-scale construction volumes, and unpredictable construction processes by adhering to two underlying empirical rules: determining the processing sequence of components based on mechanical transmission relationships, and adjusting structural priorities according to spatial functional hierarchies. This gave rise to an order and rhythm in the architecture, fostering a sense of stability and security for its inhabitants. Under the modular and flexible standard design and construction strategies, the craftsmen's innovative approaches exhibited two distinct characteristics: passive adaptive strategies under constrained construction conditions, and active technological improvements through iterative craftsmanship, forming a sustainable "standardized" craft system.

The study of flexible standard construction in traditional Chinese large-scale timber residential structures offers contemporary insights. From the phenomenon of non-textualized knowledge within traditional craftsmen's systems and construction without reliance on design drawings, we uncover the pre-20th-century "standardization" wisdom—achieving diverse construction outcomes with adaptable strategies while continuously improving technical and economic efficiency. Thus, beyond modern industrialized and automated machine-based construction, the century-old Tubao relics reveal the intrinsic driving force behind traditional builders' innovation. Master craftsmen prioritized technical strategies over design intent, skillfully employing integrative thinking to address multiple constraints—a result of their integrated design-and-construction work system. Such research not only provides a technical decoding approach for the preservation of historical architecture but also serves as a reference prototype for modern modular and flexible standard large-scale housing to adapt to nonlinear construction environments.

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