

Technology Adaptation under Heritage Constraints: A Study on the Structural Renewal Mechanism of Stone Tower Dwellings at Songgang Tianjie

Yifan Zhao

School of Architecture and Design, Southwest Minzu University, Chengdu 610225, China
Email: 957049001@qq.com

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Abstract

Converting traditional Tibetan and Qiang stone tower dwellings in western Sichuan into homestays exposes a conflict between traditional structural systems and modern functional requirements. Existing studies focus mainly on value assessment or technology enumeration, lacking a systematic account of technology selection logic. Using the stone tower dwelling relics at Songgang Tianjie, Barkam, Sichuan, as a case, this paper employs fieldwork, architectural surveying and mapping, and technical analysis to propose a triple-constraint model of “heritage conservation-structural safety-construction implementation” and to construct a technology adaptation mechanism for structural renewal. The core contradiction is the rigid constraint that walls cannot be demolished or altered despite spatial expansion needs; the solution combines original-structure-preserving reinforcement with lightweight extension continuing the relic form. The Songgang Tianjie homestay renovation verifies this mechanism and offers a reference technical path for similar relics in western Sichuan.

Keywords

Stone Tower Dwellings; Structural Renewal; Technology Adaptation; Adaptive Reuse; Songgang Tianjie

1. Introduction

Traditional stone tower dwellings on the western Sichuan Plateau, built of rubble stone and yellow clay along mountain terrain, embody Tibetan and Qiang dwelling forms and regional cultural memory. Rural revitalization and heritage conservation have recently driven many idle dwellings into adaptive reuse as homestays or cultural exhibitions. Yet accommodating modern residential and commercial functions raises a fundamental challenge: how to achieve functional transformation

while respecting heritage authenticity and ensuring structural safety. Their structural system is highly coupled---thick rubble stone walls serve as both envelope and load-bearing structure, and ribbed timber beams interlock with the walls into an inseparable network---so any single-point alteration may trigger a chain reaction. Modern needs for daylighting, spatial adjustment, sanitation, and fire evacuation therefore necessitate intervention, creating a dilemma: excessive intervention destroys heritage value, while conservative maintenance fails to meet use requirements. Focusing on homestay renewal at Songgang Tianjie, this paper addresses three questions: What are the core contradictions between traditional structural systems and modern functional requirements? How do different structural renewal technologies adapt to relic characteristics? Can an operable technology adaptation mechanism be established?

2. Technical Problem Diagnosis

2.1. Characteristics of the Stone Tower Dwelling Relics at Songgang Tianjie

Songgang Tianjie, in Barkam, Sichuan, is a well-preserved Gyalrong Tibetan stone settlement. The Tianjie winds along a mountain ridge, with tower dwellings staggered across the terrain. The research object is a typical mid-section tower dwelling: originally a three-story stone-and-timber structure with livestock on the ground floor, a hearth room in the middle, and a scripture hall and drying terrace on top, totaling about 180 m². Survey shows walls of rubble stone and yellow clay, 60-80 cm thick, tapered; integrity is acceptable but with localized mortar loss. Floors consist of closely spaced timber ribs over stone slabs and earth, with some beam ends decayed. Flat roof drainage has failed. Windows are small and few, causing severe daylight shortage. These features are typical of the typology and act as rigid constraints on adaptive reuse[1][2].



Figure 1. Location Map



Figure 2. Bird's-Eye View

2.2. Functional Requirements for Homestay Conversion

The boutique homestay scheme requires en-suite guest rooms on each floor (family

suites), ground-floor reception, light dining, and lounge areas, compliance with seismic and fire codes, and improved daylighting, ventilation, and thermal comfort. Three contradictions emerge when compared with the existing fabric.

First, structural system vs. load requirements: sanitary fixtures, pipelines, and partitions add floor loads, while original timber beams have undersized sections and degraded supports[3]. Guest rooms require exhaust vents and enlarged windows in load-bearing stone walls up to 70 cm thick; cutting these walls is difficult and may compromise overall load-bearing performance.

Second, spatial system vs. functional conversion: traditional tower dwellings are vertically zoned as “livestock below, people above, scripture hall on top,” connected by notched log ladders, creating enclosed spaces and single circulation[1]. A homestay instead requires horizontal guest-room units, connected vertical circulation, and public/private separation. The original narrow-frontage, deep-plan, few-window pattern conflicts with modern accommodation’s daylighting, ventilation, and view needs.

Third, traditional construction vs. modern technologies: rubble stone and yellow clay masonry relies on empirical knowledge without quantitative standards for mix proportions, masonry rhythm, or taper control[2]. Modern reinforcement (steel mesh-reinforced cement mortar, chemical grouting) is reliable but may alter wall breathability and appearance, or cause new damage through material incompatibility. Finding compatibility between traditional craftsmanship and modern methods is the core implementation challenge.

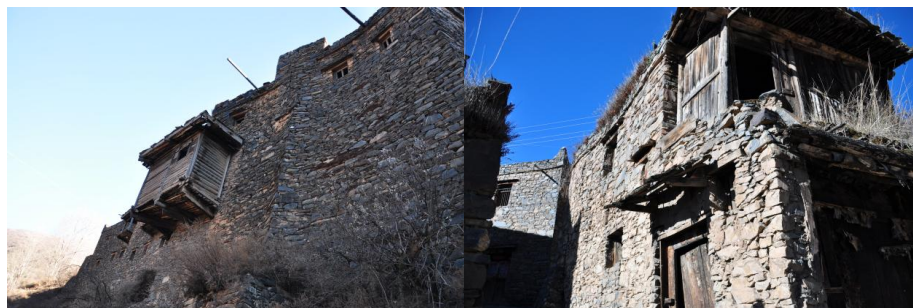


Figure 3. Walls Prior to Adaptive Reuse

3. Construction of the Technology Adaptation Mechanism

The aforementioned contradictions are intertwined, and technological choices must therefore be coordinated through a systematic adaptation framework. This paper proposes a “triple-constraint” model as the underlying logic for technology screening.

3.1. Triple-Constraint Model

The selection of structural renewal technologies for stone tower dwellings is a decision-making process under multiple heterogeneous constraints, summarized as

a “heritage conservation-structural safety-construction implementation” triple-constraint model that jointly defines the legitimate scope of intervention.

Heritage conservation is an inviolable red line, grounded in ICOMOS principles of minimum intervention and reversibility[6]. Core value elements—external stone wall texture and color, tapered wall profile, and internal original components (timber ribbed beams, notched log ladders, scripture halls)—are irreversible. Intervention must remain outside these elements or, if unavoidable, be limited to the minimum identifiable extent.

Structural safety is a non-negotiable engineering baseline. In Barkam (seismic intensity 8), the renewed building must meet three-level fortification objectives. Added loads must be reliably borne (floor live load $\geq 2.0 \text{ kN/m}^2$); the brittle stone wall-timber beam system requires enhanced integrity, shear capacity, and reliable connections; new materials must be compatible with originals and durable under plateau UV, temperature fluctuations, and long winters. Performance compromise for conservation is unacceptable.

Construction implementation concerns regional operability. Songgang Tianjie’s high semi-mountainous location allows only manual transport, requiring lightweight construction. External restoration materials have long transport cycles, and wet construction is impossible from November to March, leaving a six-month window. Skilled rubble stone artisans are scarce, while external teams lack understanding of tower dwelling structures, requiring integration of traditional craftsmanship and modern methods.

The three constraints follow incommensurable criteria: qualitative and contextual (conservation), quantitative and standardized (safety), and practical and situational (implementation). Technology adaptation seeks dynamic equilibrium within their intersection. “Optimal” means the greatest adaptation to the heritage fabric—the least disturbing path that does not transgress the red line, fall below the baseline, or exceed the boundary.

3.2. Adaptation Analysis of Core Technologies

Through a systematic review and multi-dimensional constraint-based screening, two core technologies with the highest adaptability are identified.

1) Original-structure-preserving reinforcement. Its principle is intervention without replacement, retaining the original stone wall-timber beam system. Measures: low-pressure permeation grouting and localized rebuilding of mortar joints to restore wall integrity and shear capacity[4]; mortise-and-tenon steel plates or CFRP sheets to reinforce decayed beam ends without replacement; concealed steel supporting beams beneath floors to share added loads, letting original beams retain a formal rather than primary load-bearing role. It minimally affects heritage appearance, preserves the in-situ timber frame, forms a dual load-bearing system meeting code requirements, and can be executed manually in confined spaces

without heavy machinery[5]. It is the foundational technology for structural renewal of stone tower dwellings.

2) Lightweight extension based on relic form continuation. Spatial increments unresolvable within the original shell require limited extension following formal continuation to avoid damaging the settlement skyline and typological character. A one-story “attached volume” of lightweight steel with glass and rubble stone veneer panels serves as a bathroom module on the rear or lateral side. Independent foundations and flexible joints to the old walls ensure independent seismic movement and avoid collision. Its low volume preserves the main dwelling’s height and silhouette; independent foundations and flexible connections protect wall integrity; and dismountable steel components suit mountainous transport. Its logic is not stylistic imitation but a clearly identifiable new intervention satisfying new functions while preserving the old building’s integrity.

4. Practical Validation of the Homestay Renewal at Songgang Tianjie

4.1. Overview of the Renewal Scheme

Based on the adaptation mechanism, the homestay renewal of this tower dwelling at Songgang Tianjie forms a tripartite integrated strategy of retention, reinforcement, and extension. The original three-story stone wall–timber beam main structure is fully retained, serving as the primary spatial carrier for guest rooms and public spaces. Through concealed steel supporting beams and grouting reinforcement, the overall structural performance is upgraded to current standards. On the rear side adjacent to the mountain, a row of service modules containing bathrooms and storage rooms is added as a lightweight steel structure extension, providing en-suite bathrooms for the guest rooms. Vertical circulation is resolved by a newly constructed lightweight steel staircase, and the roof of the adjacent building is utilized as the entrance to the guest rooms and a leisure terrace.

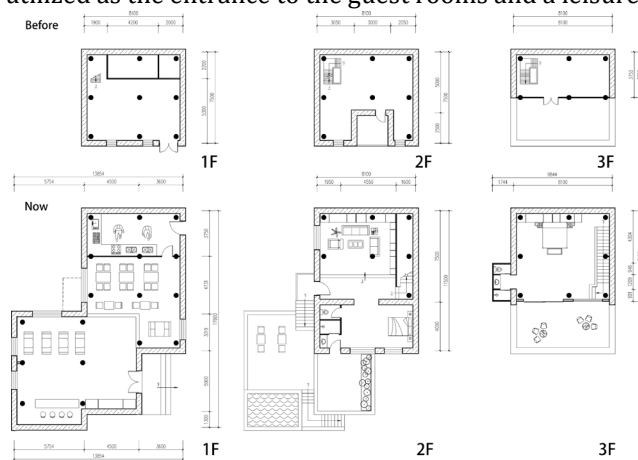


Figure 3. Floor Plans Before and After Renovation

4.2. AHP-FCE-Based Evaluation Model for Technology Adaptation Effectiveness

Existing heritage adaptive reuse projects often evaluate renewal outcomes through qualitative descriptions, making it difficult to systematically reflect the degree to which multi-dimensional constraints are satisfied, and their indicators are often characterized by fuzziness. This paper couples the Analytic Hierarchy Process (AHP) with Fuzzy Comprehensive Evaluation (FCE): AHP is used to determine weights, while FCE is employed to handle the fuzziness and uncertainty of expert judgments, thereby achieving complementarity between qualitative and quantitative approaches.

4.2.1. Evaluation Indicator System and AHP Weights

Following the triple-constraint framework established above, a three-level evaluation hierarchy of “goal level-criterion level-indicator level” is constructed. The goal level is defined as the “comprehensive effectiveness of technology adaptation for the homestay renewal of stone tower dwellings at Songgang Tianjie.” The criterion level comprises three dimensions: heritage conservation (A), structural performance (B), and functional realization (C). Each criterion is further divided into three specific indicators, totaling nine. The indicator system and the weights determined by the AHP method (group decision-making by nine experts, consistency ratio $CR < 0.1$) are presented in Table 1.

Table 1. Evaluation Indicator System and AHP Weights (Source: Author)

Criterion Level	Weight	Indicator Level	Local Weight	Composite Weight
A Heritage Conservation	0.42	A1 Integrity of Historic Character	0.48	0.20
		A2 Authenticity of Components	0.35	0.15
		A3 Reversibility of Intervention	0.17	0.07
B Structural Performance	0.35	B1 Seismic Load-Bearing Capacity	0.50	0.18
		B2 Joint Reliability	0.30	0.10
		B3 Durability	0.20	0.07
C Functional Realization	0.23	C1 Spatial Adaptability	0.42	0.10
		C2 Physical Environmental Quality	0.33	0.08
		C3 Safety and Compliance	0.25	0.06

4.2.2. Construction of the Fuzzy Comprehensive Evaluation Model

1) Comment set $V = \{\text{excellent, good, medium, relatively poor, poor}\}$, with score vector $P = (90, 75, 60, 45, 30)$. The 15-point gradient better captures grade differences than a 100-point scale and supports weighted averaging.

2) Nine AHP experts independently rated each indicator; tallied grades form membership vectors-e.g., six “excellent” and three “good” gives $(0.67, 0.33, 0, 0, 0)$. This uses the distribution of collective judgments to avoid single-score bias.

3) FCE procedure: first-level evaluation yields criterion-level membership vectors; combined with criterion weights, second-level evaluation yields the goal-level vector; weighted averaging gives the composite score, and the maximum

membership principle determines the grade.

4.3. Fuzzy Comprehensive Evaluation of the Songgang Tianjie Scheme

4.3.1. Construction of the Fuzzy Comprehensive Evaluation Model

The statistical results of the nine experts' ratings for each indicator and the summary of the membership degree vectors for each indicator are presented in Table 2. To facilitate subsequent calculations, the membership degrees of the indicators are grouped by criterion level and organized into membership degree matrices R_A , R_B , and R_C .

Table 2. Summary of Expert Ratings and Membership Degree Matrices (Source: Author)

Criterion Level	Indicator	Excellent	Good	Medium	Relatively Poor	Poor	Membership Degree Vector
A	A1 Integrity of Historic Character	7	2	0	0	0	(0.78,0.22,0,0,0)
	A2 Authenticity of Components	8	1	0	0	0	(0.89,0.11,0,0,0)
	A3 Reversibility of Intervention	5	3	1	0	0	(0.56,0.33,0.11,0,0)
B	B1 Seismic Load-Bearing Capacity	4	5	0	0	0	(0.44,0.56,0,0,0)
	B2 Joint Reliability	3	5	1	0	0	(0.33,0.56,0.11,0,0)
	B3 Durability	2	5	2	0	0	(0.22,0.56,0.22,0,0)
C	C1 Spatial Adaptability	6	3	0	0	0	(0.67,0.33,0,0,0)
	C2 Physical Environmental Quality	5	4	0	0	0	(0.56,0.44,0,0,0)
	C3 Safety and Compliance	7	2	0	0	0	(0.78,0.22,0,0,0)

From the distribution of membership degrees, no indicator was rated as “relatively poor” or “poor”, and the combined proportion of “excellent” and “good” ratings for most indicators exceeded 85%. Only three indicators—reversibility of intervention, joint reliability, and durability—received a small number of “medium” ratings, indicating that there remains room for optimization in the scheme's long-term performance and reversibility.

4.3.2. First-Level Fuzzy Comprehensive Evaluation

Let the weight vector corresponding to each first-level indicator be denoted by W_i , and the membership degree matrix by R_i . The weighted average type composition operator $M(\cdot, +)$ is adopted for the fuzzy composition operation:

$$B_i = W_i \cdot R_i. \quad (1)$$

where $B_i = (b_{i1}, b_{i2}, b_{i3}, b_{i4})$ is the fuzzy comprehensive evaluation result vector of the i -th first-level indicator; “ $\cdot$ ” denotes ordinary matrix multiplication (weighted summation).

The evaluation result vector is normalized as follows:

$$b'_{ij} = \frac{b_{ij}}{\sum_{j=1}^4 b_{ij}}, j = 1, 2, 3, 4. \quad (2)$$

1) Evaluation of the Heritage Conservation Dimension

The heritage conservation dimension (denoted as Dimension A) comprises three second-level evaluation indicators, and its weight vector is:

$$W_A = (0.48, 0.35, 0.17)$$

The membership degree matrices for the indicators are as follows:

$$R_A = \begin{bmatrix} 0.78 & 0.22 & 0.00 & 0.00 \\ 0.89 & 0.11 & 0.00 & 0.00 \\ 0.56 & 0.33 & 0.11 & 0.00 \end{bmatrix}$$

According to Eq. (1), the fuzzy composition operation is performed between the weight vector and the membership degree matrix, and the normalization condition is verified: $\sum_{j=1}^4 b_{Aj} = 0.781 + 0.201 + 0.019 + 0.000 = 1.001 \approx 1$, which satisfies the normalization requirement. According to the maximum membership degree principle, the structural performance dimension has the largest membership degree in the “excellent” grade (0.781); therefore, the evaluation grade of this dimension is excellent.

2) Evaluation of the Structural Performance Dimension

The structural performance dimension (denoted as Dimension B) comprises three second-level evaluation indicators, and its weight vector is:

$$W_B = (0.50, 0.30, 0.20)$$

The membership degree matrices for the indicators are as follows:

$$R_B = \begin{bmatrix} 0.44 & 0.56 & 0.00 & 0.00 \\ 0.33 & 0.56 & 0.11 & 0.00 \\ 0.22 & 0.56 & 0.22 & 0.00 \end{bmatrix}$$

According to Eq. (1), the fuzzy composition operation is performed between the weight vector and the membership degree matrix, and the normalization condition is verified: $\sum_{j=1}^4 b_{Bj} = 0.363 + 0.560 + 0.077 + 0.000 = 1.000$, which satisfies the normalization requirement. According to the maximum membership degree principle, the structural performance dimension has the largest membership degree in the “good” grade (0.560); therefore, the evaluation grade of this dimension is good.

3) Evaluation of the Functional Realization Dimension

The functional realization dimension (denoted as Dimension C) comprises three second-level evaluation indicators, and its weight vector is:

$$W_C = (0.42, 0.33, 0.25)$$

The membership degree matrices for the indicators are as follows:

$$R_C = \begin{bmatrix} 0.67 & 0.33 & 0.00 & 0.00 \\ 0.56 & 0.44 & 0.00 & 0.00 \\ 0.78 & 0.22 & 0.00 & 0.00 \end{bmatrix}$$

According to Eq. (1), the fuzzy composition operation is performed between the weight vector and the membership degree matrix, and the normalization condition is verified: $\sum_{j=1}^4 b_{Cj} = 0.661 + 0.339 + 0.000 + 0.000 = 1.000$, which satisfies the normalization requirement. According to the maximum membership degree principle, the functional realization dimension has the largest membership degree in

the “excellent” grade (0.661); therefore, the evaluation grade of this dimension is excellent.

The fuzzy comprehensive evaluation results of the three dimensions are summarized as follows:

Table 3. Summary Table of Fuzzy Comprehensive Evaluation Results for the Three Dimensions (Source: Author)

Evaluation Dimension	Excellent	Good	Medium	Poor	Evaluation Grade
Heritage Conservation Dimension A	0.781	0.201	0.019	0.000	Excellent
Structural Performance Dimension B	0.363	0.560	0.077	0.000	Good
Functional Realization Dimension C	0.661	0.339	0.000	0.000	Excellent

As shown in the table, both the heritage conservation dimension and the functional realization dimension are rated as excellent, whereas the structural performance dimension is rated as good. In particular, the membership degree of the structural performance dimension in the “excellent” grade is only 0.363, markedly lower than those of the other two dimensions, indicating that this dimension constitutes a key direction for subsequent optimization and improvement.

4.3.3. Second-Level Fuzzy Comprehensive Evaluation

The membership degree vectors of the three criterion levels are assembled into a new evaluation matrix R , which is then subjected to a composition operation with the criterion-level weight vector $W = (0.42, 0.35, 0.23)$.

$$R = [B_A; B_B; B_C]$$

$$= [[0.781, 0.201, 0.019, 0, 0], [0.363, 0.560, 0.077, 0, 0], [0.661, 0.339, 0, 0, 0]]$$

$$B_{total} = W \cdot R = (0.607, 0.358, 0.035, 0, 0)$$

The comprehensive membership degree vector B_{total} indicates that the technology adaptation effectiveness of the project has a membership degree of 0.607 for “excellent,” 0.358 for “good,” and 0.035 for “medium,” with no evaluations at the “relatively poor” or “poor” levels.

4.3.4. Comprehensive Score and Grade Determination

The composite score is calculated using the weighted average method: $S = B_{total} \times P^T = 0.607 \times 90 + 0.358 \times 75 + 0.035 \times 60 = 54.63 + 26.85 + 2.10 = 83.58$ points. According to the maximum membership degree principle, the largest component in B_{total} , 0.607, corresponds to the “excellent” grade. Therefore, the comprehensive effectiveness of technology adaptation for the homestay renewal scheme of the stone tower dwellings at Songgang Tianjie is rated as “excellent.” Meanwhile, the composite score of 83.58 points falls within the transitional interval from the mid-range of “good” to the lower margin of “excellent,” indicating that the scheme

achieves excellent overall effectiveness but still has room for improvement.

4.4. Evaluation Results and Implications

AHP-FCE results validate the adaptation mechanism. Heritage conservation has the highest “excellent” membership (0.781), aligning with conservation priority. Functional realization is dominated by “excellent” (0.661), showing effective conversion under strict conservation. Structural performance is dominated by “good” (0.560), with the highest “medium” (0.077), dragged down by durability (B3, 0.22) and joint reliability (B2, 0.11). This reflects a deep-seated contradiction: uncertainty in long-term reinforcement performance and joint fatigue makes “excellent” difficult to substantiate, requiring long-term monitoring.

AHP-FCE accommodates indicator fuzziness and multi-dimensional constraints in heritage evaluation. The comprehensive vector (0.607, 0.358, 0.035, 0, 0) offers richer information than a single score: ~60% “excellent” and ~40% “good,” with confidence concentrated in high grades and controllable risk. This probabilistic expression is more decision-useful than precise AHP scores and aligns with the precautionary principle of heritage intervention.

5. Conclusion

Starting from practical difficulties in the adaptive reuse of stone tower dwellings in western Sichuan, this study of the Songgang Tianjie relics concludes:

(1) Core technical contradictions reduce to three oppositions-spatial expansion vs. rigid walls that cannot be altered, increased loads vs. insufficient structural capacity, and modern methods vs. incompatible traditional materials-rooted in the structural system’s high integrity, where any localized alteration entails systemic risk.

(2) thematic adaptation mechanism. The triple-constraint model and the cycle of characteristic diagnosis-requirement input-constraint screening-technology matching-effect evaluation provide a structured framework, placing technology within the three-dimensional coordinates of heritage conservation, structural safety, and implementation conditions, thus avoiding single-dimension over-optimization[7][8].

(3) The Songgang Tianjie practice shows that a combination of original-structure-preserving reinforcement and lightweight extension achieves contemporary functional conversion while preserving historic character, offering wider application value for similar relics on the western Sichuan Plateau.

Limitations remain: long-term performance-especially grouting material compatibility with rubble stone walls and durability of lightweight structures under extreme climate-requires continuous monitoring. Future research can expand case samples and establish a more universally applicable decision matrix for technology adaptation[4][5].

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