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Structural Redundancy Degradation and Critical Intervention Threshold: Conservation Decision-Making for the Nationally Protected Shunde Bridge

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Abstract: In traditional heritage conservation, the principle of "minimum intervention" often ends up being applied subjectively because there are no clear quantitative benchmarks. This study introduces a "structural redundancy degradation model" along with a "critical intervention threshold" theory. Together they shift safety assessments of historic timber buildings from qualitative descriptions to quantitative evaluations based on material decay, accumulated deformation, and leftover load-bearing capacity. Using Shunde Bridge—a nationally protected heritage site—as an example, we systematically assessed the loss of redundancy in each component of its wooden arch frame. We used 3D laser scanning, resistograph testing, and manual surveys. The results show that: inside the three-segment rafter A-2, 49% of the cross-section has failed, and its load-bearing redundancy is close to zero; component A-5 has completely lost function; termite damage at the end of the bull-head timber exceeds one quarter of the cross-section, causing local redundancy loss; the overall tilt of the bridge's covered corridor (110 mm) has seriously reduced the system's structural redundancy. Based on this theory, we determined that Shunde Bridge has already passed the "local repair threshold" and reached the "system-level dismantling threshold." This gives a quantifiable, evidence-based reason for deciding to fully dismantle and carry out a major repair. Our work shows that the redundancy degradation model can fill the practical gap left by the minimum intervention principle in cases of extreme deterioration. It also offers a scientific framework for deciding when and how much to intervene in similar wooden heritage structures.

Keywords: Structural Redundancy; Critical Intervention Threshold; Wooden Arch Lounge Bridge; Shunde Bridge; Complete Dismantling and Major Repair; Principle of Minimum Intervention.

1. Introduction

The "minimum intervention" principle has long been central to cultural heritage conservation, and in theory it is ethically sound [1]. The idea is to keep as much original historic material as possible and to avoid over-repair or needless replacement. But when a historic timber structure has serious, fast-advancing decay, what does "minimum intervention" actually mean? Should we do cautious local repairs, or a complete but thorough restoration? This puzzle comes up again and again in everyday conservation work.The core issue is that traditional conservation thinking lacks any quantitative way to describe a structure's "safety margin." Decisions about intervention often rely on gut feeling and experience. That can lead to two bad outcomes: either "patch-up" repairs that miss the best time to act, or too much intervention that damages the heritage's authenticity [2].In this paper we try to bring in the engineering concept of "redundancy" and turn it into an analytical tool suitable for old timber structures [3,4]. We also put forward a "critical intervention threshold" model. The idea is: when the redundancy of a key component or the whole system drops below a certain value, sticking to local repairs can no longer restore safety. In fact, repeated small interventions may add up and even speed up deterioration. In such a situation, full dismantling and thorough repair is actually the choice that best follows the spirit of "minimum intervention." To test our theory, we used Shunde Bridge, a nationally protected heritage site, as a case study. We gathered quantitative data from 3D laser scanning, resistograph tests, and careful on-site surveys. Using that data we evaluated the loss of redundancy step by step—both in individual components and in the whole structure. From this we identified which intervention threshold the bridge has now reached, and thus provided a repeatable, theory-based justification for a full dismantling and major repair.

2. Theoretical Framework: Structural Redundancy and Critical Intervention Threshold

2.1. Definition of Structural Redundancy and Its Applicability to Heritage Timber Structures

In structural engineering, "redundancy" describes how well a system can stay stable and continue carrying loads after some local parts fail. A highly redundant structure can still find alternative load paths even after losing one or several key members, and so avoids immediate collapse. Modern reinforced concrete designs often achieve redundancy through multiple load-transfer routes.But for ancient woven-arch structures like wooden arch lounge bridges [5], redundancy works quite differently. The load-bearing behaviour of a wooden woven arch does not rely on "extra" members standing by. Instead it depends on tight mortise-and-tenon compression and mutual restraints between parts to form an integral arch shape. Each three-segment rafter, five-segment rafter, and bull-head timber has an irreplaceable role in the arch frame, providing geometric constraints and transferring loads [6].Strictly speaking, the "redundancy" of a wooden arch bridge appears in this way: as long as elastic deformation stays within limits, local damage can be temporarily balanced by the cooperation of nearby members. But that cooperative ability degrades quickly as materials decay and joints loosen. In this paper we define the "structural redundancy" of a wooden arch lounge bridge as: the amount of local performance loss or component failure that the whole system can tolerate without going into irreversible overall instability. In practice it is roughly estimated by the "ratio of remaining load-bearing capacity to design demand" or the "proportion of sound area in a critical cross-section."

2.2. Dual Dimensions: Material Redundancy and Geometric Redundancy

For easier analysis, we split redundancy into two related dimensions. Material redundancy refers to the proportion of still-sound, load-bearing material inside a single timber component's cross-section. The resistance curves from a resistograph can be turned into a wood-density profile along the drilling depth, letting us estimate how much cross-section has been lost to rot, insects, etc. When the length over which the resistance value at the end of an inclined rafter stays below 80 (Level 5 failure) exceeds one third of the cross-section diameter, we can consider its material redundancy to be near zero.Geometric redundancy means how much the overall shape of the structure has deviated from its original design geometry. The mechanical performance of a wooden arch bridge depends heavily on the geometry of the arch axis. Crown settlement, bull-head timber displacement, and leaning columns all change the load paths, create extra bending moments, and make mortise-and-tenon joints pull out faster. Loss of geometric redundancy shows up as deformation beyond the elastic recovery range, with the deformation rate speeding up.When both material redundancy and geometric redundancy drop sharply at the same time, the structure is on the verge of systemic instability.

2.3. Definition of Critical Intervention Thresholds

Based on the two-dimensional redundancy assessment described above, we propose a three-level intervention threshold system (Table 1).

Level 1 – Routine maintenance threshold: material redundancy > 0.9, geometric deformation ≤ 10 mm. Only regular inspections, roof cleaning, and drainage clearance are needed. No component replacement. Level 2 – Local repair threshold: material redundancy of individual components falls to 0.5–0.7, geometric deformation ≤ 30 mm. Local measures like patching, iron bands, or stilt repair can be used. The overall structure still has self-balancing ability; replacing a whole component would be unnecessary intervention. Level 3 – System-level dismantling threshold: material redundancy of key load-bearing parts (e.g., three-segment rafters, bull-head timbers) drops below 0.3, and geometric deformation exceeds 50 mm and is still getting worse. Local repairs can no longer bring back safe redundancy. Replacing a single member would create new stress concentrations because of stiffness differences between old and new wood and because of residual deformation. At this point, the only effective conservation approach is full dismantling, followed by systematic straightening and repair of the foundation, arch frame, and covered corridor.Survey data from Shunde Bridge show that the bridge has clearly passed the second threshold and entered the third threshold range.

Table 1. Three-level threshold system for timber structure intervention

Threshold Level	Material Redundancy (critical members)	Geometric Deformation (max inclination/settlement)	Intervention Strategy
Level 1(Routine Maintenance)	≥0.9	≤10 mm	Periodic inspection,roof cleaning, drainage clearing
Level 2(Local Repair)	0.5-0.7	≤30 mm	Patching,iron hoop reinforcement,local splicing
Level 3(Systematic Dismantling Overhaul)	≤0.3	≥50 mm and progressive	Full dismantling,foundation resetting,arch frame correction

3. Quantitative Assessment of Structural Redundancy of Shunde Bridge

3.1. Survey Methods and Data Acquisition

To get precise numbers for material and geometric redundancy, we used three complementary techniques.

3D laser scanning (Trimble TX8): produced a point-cloud model of the whole bridge [7]. By cutting sections we extracted geometric parameters like deck elevation, column-top 3D coordinates, and relative height differences of bull-head timber top surfaces, achieving millimetre accuracy.Resistograph (tree-drilling needle tester): assessed internal material degradation of key timber parts [8]. A 3-mm-diameter steel needle was driven into the wood at constant speed, recording resistance variation with depth. Following standard procedures, wood condition was divided into five levels (Level 1: good ≥ 200; Level 2: fairly good 160–200; Level 3: average 120–160; Level 4: poor 80–120; Level 5: failed < 80).Traditional visual inspection and tapping: used as backup to examine each inclined rafter, bull-head timber, and column, paying special attention to iron rust and added shims from the 2008 restoration.All data were cross-checked and entered into a database for quantitative calculation of redundancy indicators.

3.2. Material Redundancy Analysis: Cross-Section Deterioration Assessment of Three-Section Seedlings

The three-segment rafter arch carries the most direct load and is the most concentrated load-transfer point in Shunde

Bridge. Resistograph results gave the following:

East inclined rafter A-2: over a 350 mm length from the end, the average resistance was only 117. Level 5 failure segments (resistance < 80) accounted for 49%, and Level 4 poor segments (80–120) for 20%. In cross-section terms, about half of the end area had lost load-bearing capacity, with spongy termite tunnels inside; the remaining sound wood could not properly transfer the thrust from the arch foot.A-5: end average resistance even lower at 91, with Level 5 segments making up 58%; the member had visibly fractured and was temporarily supported with steel pipes on site.West inclined rafter C-1: end average resistance 107, with Level 4 poor segments 67%. Although not completely broken, decay over a 1.2 m length at the root had reduced the effective cross-section diameter by about 40%.C-7: end average resistance 131 (Level 3, average), Level 4 segments 21%; but 1.5 m from the end the average resistance rose to 174 (Level 2, fairly good), with Level 4 down to 9%. This shows that C-7's deterioration is mostly within the end 1.5 m; further in the material is still sound.

Overall, the material redundancy of A-2, A-5, and C-1 fell below 0.3, reaching or even going under the system-level dismantling threshold. Although C-7 is not completely failed, its end deterioration is serious.Resistograph tests on the bull-head timbers revealed hidden damage. At the west bull-head timber end (measurement points 16-18), the average resistance was only 107, with Level 5 segments 26% and Level 4 segments 67%. That means extensive termite damage where the bull-head timber end meets the inclined rafters. Since the bull-head timber turns the horizontal thrust from both sides into vertical distribution, losing material redundancy at its end directly hurts the integrity of the whole arch frame. Together with visible 10 mm cracks and marks from 2008 iron bands embedded into the wood, we estimate that the effective load-bearing cross-section of this bull-head timber is less than 60% of the original, with material redundancy around 0.35—also in the range that requires replacement or heavy reinforcement.

Table 2. Impedance testing and redundancy assessment of critical diagonal members (three-segment arch)

Member ID	Test Position	Test Length (mm)	Impedance Mean	Grade V (Failed)Proportion	Grade IV (Poor)Proportion	Estimated Material Redundancy	Conclusion
A-2	End(0m)	359	117	49%	20%	0.21	Severe decay, needs replacement
A-2	0.5 m from end	353	144	0%	30%	0.55	Relatively poor,splicing possible
A-5	End(0 m)	379	91	58%	10%	0.12	Already fractured,must replace
C-1	End(0 m)	328	107	0%	67%	0.28	Root decay,needs replacement
C-7	End(0m)	330	131	0%	21%	0.48	End decay,splicing suggested
C-7	1.5m from end	328	174	0%	9%	0.82	Wellpreserved,can retain

3.3. Geometric Redundancy Analysis: Deformation Accumulation and Structural Imbalance

The 3D laser scanning data revealed the geometric deformation of the covered corridor and the wooden arch frame. Main geometric parameters are summarised in Table 3.

The bridge-deck top elevation measurements showed a 0.51 m height difference between the east and west abutment padstones (west higher, east lower). This matched the 2008 as-built drawings, so it came from the original uneven foundation layout, not from later settlement. However, the covered corridor as a whole had a clear north–south tilt: at axis 3, the north–south column-top height difference reached 110 mm, with the north side higher. This indicates that the timber frame had twisted under long-term loading.

Looking more closely at bull-head timber top elevations: the north end of the west three-segment rafter's bull-head timber was 0.06 m lower than the south end, and the north end of the west five-segment rafter's upper bull-head timber was 0.04 m lower than the south end. That means the wooden arch itself had settled unevenly—it was not just the corridor that deformed.

A key sign of geometric redundancy loss is the "deviation of the arch axis." By comparing our 3D model sections with the ideal arch shape recorded in the Daoguang period bridge-building contract (no original drawings exist, but we could infer the shape from still-well-preserved symmetrical parts), we found that the east arch foot had subsided much more than the west arch foot, and the arch crown centreline had moved about 85 mm from its original position. This deviation caused extra bending moments at the mortise-and-tenon joints between inclined rafters and bull-head timbers, leading to multiple tenon withdrawals (columns and beams at axes B and C had pulled out by 5–25 mm) and misaligned bull-head timber joints.

Geometric redundancy can be quantified as the "ratio of current deformation to the structure's elastic recovery limit." According to the Technical Standard for Maintenance and Reinforcement of Ancient Wooden Structures, when column tilt exceeds 50 mm and deformation is still developing, it should be considered a precursor to instability. Shunde Bridge's 110 mm tilt is far beyond that, and a comparison of two measurements from 2022 and 2023 showed no slowdown in the deformation rate. Therefore geometric redundancy is essentially zero.

Table 3. Key geometric deformation data of Shunde Bridge

Measurement Item	North/West Side	South/East Side	Height Difference	Assessment
Abutment cushion stone elevation	West abutment+0.75m	East abutment±0.00 m	0.51m(west higher)	Original difference,not settlement
West corbel top elevation(three-segment arch)	Elev.4.79 m	Elev.4.85 m	0.06m(south higher)	Uneven settlement
West upper corbel top elevation (five-segment arch)	Elev.5.11 m	Elev.5.15m	0.04m(south higher)	Uneven settlement
Column top at axis 3	North reference	South 110 mm lower	110 mm	Overall northward tilt
Mortise-tenon joint gaps	Axes B,C	5-25 mm gaps	Multiple locations	Loose connections

3.4. Cross-Dimensional Diagnosis: Comprehensive Assessment of System Redundancy

By cross-analysing material redundancy and geometric redundancy in a matrix, we obtained the overall system redundancy grade. Table 4 summarises the assessment for each key location.

Material redundancy of A-2 and A-5 is below 0.3, that of C-1 below 0.35, and that of the west bull-head timber below 0.35. These key components no longer have independent load-bearing capacity. At the same time, overall geometric redundancy is seriously reduced because of the 110 mm tilt and uneven bull-head timber settlement.

According to the "redundancy-stiffness" relationship in structural mechanics, when both the material redundancy of key parts and the system's geometric redundancy fall below 0.5, replacing individual parts not only fails to improve overall stiffness but can actually create new stress concentrations because of elastic modulus differences between old and new wood and because residual deformations are incompatible. The lesson from the 2008 restoration confirms this: some inclined rafters and bull-head timbers were replaced then, but the arch frame's geometric deformation was not fully corrected. Barely a decade later, the deformation returned and was even worse.

Using the critical intervention threshold model we established, Shunde Bridge has clearly passed the "local repair threshold" and entered the "system-level dismantling threshold." Its status under the Technical Standard for Maintenance and Reinforcement of Ancient Wooden Structures is: foundation – Grade B (relatively stable); upper load-bearing structure – Grade C (seriously fails to meet Grade A requirements, affecting overall load capacity); enclosure system – Grade B. Given the quantitative redundancy data in Table 4, a systematic full dismantling and major repair must be carried out.

Table 4. Comprehensive redundancy assessment of Shunde Bridge system

Component/Locat	Material Redundancy	Geometric Redundancy (deformation)	Comprehensive Redundancy	Threshold Determination
Three-segment arch A-2	0.21	--	0.21	Systematic dismantling
Three-segment arch A-5	0.12	--	0.12	Systematic dismantling
Three-segment arch C-1	0.28	--	0.28	Systematic dismantling
Three-segment arch C-7	0.48(end)	--	0.48	Local repair
West corbel	0.35	10 mm misalignment	0.35	Systematic dismantling
Entire covered corridor	--	110 mm tilt	~0.20	Systematic dismantling
System overall	Mean of critical members<0.30	Deformation>2×limit	**0.20-0.25**	**Systematic dismantling required**

4. Threshold-Based Intervention Strategy Design

4.1. Re-demonstration of the Necessity of Complete Dismantling and Major Repair

Under the redundancy-degradation framework, the case for full dismantling and major repair can be restated like this: when system redundancy falls below a certain critical value (we propose 0.3), the structure has lost its self-balancing ability. Any local repair that does not involve comprehensive disassembly cannot bring back redundancy. Instead, repeated small interventions may cause cumulative damage to the historic fabric.

For Shunde Bridge, A-2, A-5, and C-1 have essentially failed, termite damage at the bull-head timber end exceeds one quarter of the cross-section, and the 110 mm tilt is still getting worse. Estimated system redundancy is between 0.20 and 0.25. In this situation, a conservative approach like "jack-based straightening with repacking and selective component replacement" would require temporary support for the arch frame during construction. But such support cannot eliminate the existing deformations, and after replacement, the new and old members will inevitably have initial stresses. After a few wet-dry cycles and loading events, the deformation would reappear. The 2008 restoration already proved this empirically.

Therefore, full dismantling and major repair does not abandon the principle of minimum intervention. Instead, it reinterprets minimum intervention under the guidance of redundancy degradation theory. For heritage structures in the third threshold range, the smallest and most effective intervention is a thorough, systematic restoration.

4.2. Core Restoration Measures

The detailed procedures of full dismantling and major repair are closely linked to the redundancy assessment results for each component. Table 5 summarises the restoration strategies for main components. For members with material redundancy below 0.3 (A-2, A-5, C-1, west bull-head timber): complete replacement. New timber shall be naturally aged Chinese fir at least 60 years old, with strength grade no lower than TC15. Fast-grown young fir is strictly forbidden.For members with redundancy between 0.3 and 0.5 (e.g., the end of C-7): stilt repair or steel-sleeve reinforcement, keeping most of the original material.For members with redundancy above 0.5 (e.g., A-1, A-4, C-3, etc.): after dismantling, clean surface dirt, apply anti-insect and anti-decay impregnation, and reinstall in original positions.

All iron bands and steel plates added during the 2008 restoration shall be removed after evaluation. New 5 × 50 mm galvanised flat iron bands shall be used, installed in graded numbers according to redundancy loss: six bands for three-segment rafter bull-head timbers, two bands at ends of five-segment rafter bull-head timbers, and one band at fractured ends of inclined rafters. All iron components shall receive fluorocarbon anti-rust coating, with surface colour matched to the wood (chestnut brown).

Table 5. Main component intervention strategies based on redundancy assessment

Component ID/Location	Material Redundancy	Current Damage	Intervention Measure	Material/Processing Requirement
A-2	0.21	70%termite damage, sponge-like interior	Full replacement	60+year natural old China fir
A-5	0.12	Already fractured, temporary steel prop	Full replacement	60+year natural old China fir
C-1	0.28	1.2 m root decay	Full replacement	60+year natural old China fir
C-7	0.48(end)	End decay, interior sound	Steel sleeve splicing (0.4-0.8m)	Preserve most original material
West corbel	0.35	End termite damage>1/4 section,10 mm crack	Full replacement or deep patching	Depends on inspection after opening
East corbel	To be verified	Hidden termite damage under steel plate	Open steel plate for inspection	Patch if minor, replace if severe
E-6/E-5	0.55	400 mm end cracks	Add one 5×50 mm iron hoop	Retain original member
High-redundancy diagonals	>0.70	Well preserved	Reinstall in original position	Immersion treatment for insect and decay prevention

4.3. Core Restoration Measures (continued)

The geometric redundancy restoration of the foundation pad stones primarily involves repositioning and straightening. The 0.51m height difference between the east and west abutment pad stones has been confirmed as original through historical comparison and will not be artificially altered. However, later heterogeneous stone materials such as granite added as patching shall be removed, and fine-grained stone shall be restored according to the original craftsmanship. The geometric redundancy restoration of the lounge column grid shall be achieved after dismantling by adjusting the thickness of the pad blocks beneath the columns, recalibrating the purlin specifications (Φ120–140mm), and correcting the overall tilt of the beam frame. The roof shall be stripped and re-tiled, with 30% of the bottom tiles and 40% of the covering tiles replaced, giving priority to locally sourced old tiles. Later cement ridge tiles shall be removed, and the ridge restored with blue brick masonry and lime-mortar plastering, thereby improving the redundancy of the enclosure system and preventing rainwater infiltration from accelerating timber deterioration. For termite control, a dynamic monitoring system shall be introduced, with 36 monitoring points arranged around the periphery of the bridge abutments, connected to a remote early warning platform, so that the degradation of redundancy caused by biological erosion can be kept within an acceptable range.

5. Discussion: Implications of Redundancy Theory for Conservation Practice

5.1. Moving from Experience-based Judgment to Quantitative Decisions

In traditional conservation, the question "should we fully dismantle?" often leads to debates based on experts' personal experience, with no shared criteria. The redundancy degradation model bases decisions on measurable indicators: material redundancy from resistograph values, geometric redundancy from 3D scanning deformation data. Table 6 compares the three-level thresholds with Shunde Bridge's measured data, clearly showing that the bridge has completely crossed the second threshold and entered the third level.

The Shunde Bridge case suggests that when the average resistograph value of key components consistently falls below 80, the length of failed segment exceeds one third of the cross-section diameter, and overall tilt exceeds 50 mm, any local repair is very unlikely to work. This quantitative framework can be extended to other wooden heritage structures; the threshold parameters can be adjusted according to each structure's material properties, span, load conditions, etc. Of course, thresholds are not absolute—they need fine-tuning with heritage value assessment and risk tolerance—but they provide a common basis for discussion among all parties involved.

Table 6. Comparison of measured data from Shunde Bridge with three-level thresholds

Indicator	Level 1 (Routine Maintenance)	Level 2 (Local Repair)	Level 3 (Systematic Dismantling)	Measured Value at Shunde Bridge	Determination
Minimum material redundancy of any member	≥0.9	0.5-0.7	≤0.3	0.12(A-5)	Level 3
Typical material redundancy of critical members	≥0.9	0.5-0.7	≤0.3	0.21(A-2),0.28(C-1)	Level 3
Maximum column inclination	≤10 mm	≤30 mm	≥50 mm and progressive	110 mm	Level 3
Maximum mortise-tenon gap	None	≤10 mm	≥15 mm	5-25 mm (multiple locations)	Level 3
Corbel uneven settlement	≤5 mm	≤15 mm	≥30 mm	40-60 mm	Level 3

5.2. Rethinking the Minimum Intervention Principle

This paper does not intend to deny the minimum intervention principle. On the contrary, redundancy theory is actually its operational extension. The ultimate goal of minimum intervention is “to preserve heritage value as much as possible.” When system redundancy is still within the local repair threshold, replacing an inclined rafter that still has 60% sound material would itself be excessive intervention. But when redundancy has fallen below the system-level dismantling threshold, persisting with local repairs will only put the heritage in critical danger or even cause collapse within a few years—that would be the greatest damage to its value.

So conservation practitioners should distinguish between the “extent of intervention” and the “necessity of intervention.” What Shunde Bridge needs is a “high-extent but low-frequency” one-time intervention, not a “low-extent but high-frequency” series of repeated repairs. Over a life-cycle perspective, one successful full dismantling and major repair may keep the structure stable for more than fifty years, whereas multiple local repairs could result in a larger total amount of intervention and more disturbance to the heritage. Redundancy theory gives a quantitative foundation for this judgement.

5.3. The Integrated Value of Technical Means

This case successfully shows how 3D laser scanning and resistograph testing complement each other in wooden heritage conservation. 3D scanning excels at capturing macroscopic geometric deformation, while the resistograph is excellent for diagnosing microscopic material degradation. Together they allow simultaneous assessment of geometric and material redundancy. In the future, stress-wave tomography or continuous profile analysis with micro-drill resistographs could be introduced to refine the layered assessment of redundancy even further. The cost of these technologies is falling, and they should become standard equipment for regular “physical exams” of nationally protected and higher-level wooden heritage structures, helping shift from emergency repair to preventive conservation.

6. Conclusion

To address the difficulty of quantitatively applying the “minimum intervention” principle in historic timber structure conservation, this paper proposed a “structural redundancy degradation model” and a “critical intervention threshold” theory. The theory divides structural safety conditions into three levels: routine maintenance threshold, local repair threshold, and system-level dismantling threshold. It assesses them quantitatively through two dimensions—material redundancy (cross-section deterioration rate from resistograph) and geometric redundancy (deformation from 3D scanning).

Using the nationally protected Shunde Bridge as a case study, the survey data show:For three-segment rafter A-2, internal failed section 49%, material redundancy 0.21.A-5 has fractured, redundancy 0.12.C-1 root average resistograph value 107, redundancy 0.28.West bull-head timber end termite damage exceeds one quarter of cross-section, redundancy 0.35.Overall covered corridor tilt 110 mm, geometric redundancy near zero.

These indicators mean the bridge’s system redundancy has fallen to between 0.20 and 0.25, far below the local repair threshold (0.5–0.7), making full dismantling and major repair unavoidable. The restoration measures designed based on this theory—completely replacing components with redundancy near zero, reinforcing moderately degraded ones, keeping high-redundancy components, and correcting geometric deformation—achieve both maximal preservation of heritage value and the most reliable structural safety.

This study provides a quantifiable and repeatable theoretical framework for intervention decisions in the conservation of wooden arch lounge bridges and other complex wooden heritage structures. It can help move the principle of minimum intervention from an ethical ideal towards scientific practice.

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