

Supplementary Information

Introduction to Yunyan Temple Pagoda

Yunyan Temple Pagoda, commonly known as Tiger Hill Pagoda, was constructed between the sixth year of the Xiande reign of the Later Zhou dynasty and the second year of the Jianlong reign of the Northern Song dynasty.

The pagoda has a north–south diameter of approximately 13.8 m at ground level and approximately 8.2 m at the seventh level. Its octagonal profile tapers gradually upward, with a surviving structural height of approximately 47 m. The masonry body consists of an outer wall, a circumambulatory corridor, an inner wall, and a central core chamber. Parts of the original upper finial have been lost.

Background of the Yunyan Temple Pagoda Restoration

The archival source report refers to major restoration and reinforcement works completed in 1987, whereas other project records identify the principal foundation–stabilisation campaign as having been completed in 1986. Subsequent monitoring indicated that the pagoda remained generally stable, although several material, environmental, and maintenance-related problems became increasingly apparent over time.

Underlying deterioration factors:1.Long-term exposure of the pagoda masonry to wind-driven rain;2.Freeze–thaw deterioration of exposed masonry components; 3.Limited resistance of the masonry envelope to rainwater penetration.

Visible deterioration conditions: 1.Surface weathering of the masonry; 2.Leakage at the pagoda top; 3.Corrosion-induced expansion and cracking around earlier steel reinforcement; 4.Loss of bricks from the eaves; 5.Vegetation growth in masonry joints; 6. Rainwater penetration through open joints and cracks.

Damage condition before repairs to the Yunyan Temple Pagoda

1. An incomplete lightning-protection system. 2. Severe corrosion and expansion of the steel plates embedded within the corner masonry columns. 3. Limited resistance of the masonry to rainwater penetration. 4. Freeze–thaw deterioration and loss of bricks from the eaves. 5. Vegetation and root growth within masonry joints. 6. Cracking associated with corrosion of earlier reinforcement and rainwater penetration. 7. Deformation and partial instability of arched openings. 8. Severe material loss beneath the projecting eaves. 9. Inadequate surface drainage around the base of the pagoda.

Principles and basis for the maintenance and upkeep of Yunyan Temple

Following an on-site condition survey, the maintenance strategy was developed in accordance with the Principles for the Conservation of Heritage Sites in China and the specific heritage characteristics of the Yunyan Temple Pagoda. The project adopted the principles of retaining the existing historic condition, minimum intervention, material compatibility, and improvement of the surrounding conservation environment.:

Principle of retaining the existing historic condition: Necessary protective measures were introduced without unnecessarily altering the surviving appearance, material characteristics, or historic evidence of the pagoda. Interventions were limited to deteriorated areas and components requiring maintenance or risk reduction.

Principle of minimum intervention: Priority was given to improving the conservation environment and controlling the causes of deterioration. Direct intervention in the historic fabric was limited to areas where it was technically necessary.

Owing to the pronounced inclination and octagonal geometry of the Yunyan Temple Pagoda, a project-specific scaffolding system was designed by specialist engineers. The leaning profile increased the complexity of scaffold erection and required substantially more structural members than would normally be necessary for a vertically aligned pagoda.



Lightning protection works

The existing lightning rod was cleaned and polished to remove surface corrosion products and restore electrical conductivity.



Before polishing



After polishing

The original down conductor consisted of a single bare copper conductor with a relatively small cross-sectional area. During the maintenance project, it was replaced with two 100 mm² copper down conductors to improve electrical conductivity, reliability, and safety.

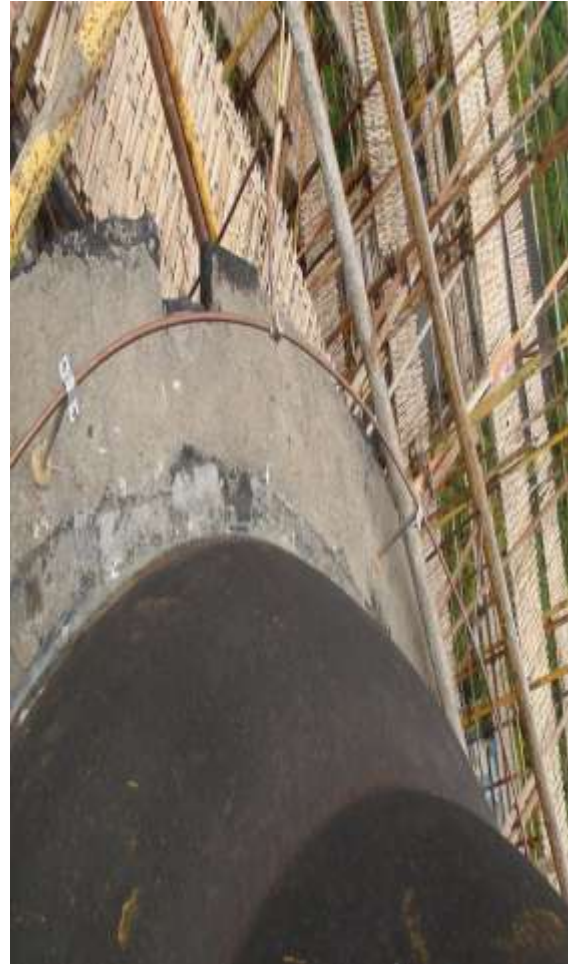


Before replacement



After replacement

Four circumferential lightning-protection bands were installed at key levels of the pagoda to improve the continuity and effectiveness of the lightning-protection system.



Installation of a circumferential lightning-protection band around the inverted-bowl element of the finial



Installation of a circumferential lightning-protection band at the seventh level



Installation of a circumferential lightning-protection band at the fifth-level eave-brick zone



Installation of a circumferential lightning-protection band at the sixth-level eave-brick zone

The original lightning-protection system did not include step-voltage protection. The 2015 intervention therefore introduced a step-voltage protection system around the grounding area of the pagoda.



step-voltage protection



exothermic welding



Insulated asphalt backfill for
step-voltage protection



Lightning-protection
inspection box

Vegetation removal

Vegetation growing within the masonry joints and on the upper external surfaces was first inactivated and carefully removed, including the associated root systems.



Maintenance of the pagoda finial and upper protective layers



Cracking and detachment of the protective coating around the lightning-rod installation point



Detached and cracked areas were repaired using crack-resistant and water-resistant repair mortar.



Detachment of the protective surface layer from the inverted-bowl element of the finial



Reinstatement of the protective surface layer on the inverted-bowl element

Maintenance of corner steel plates

Circumferential steel hoops and corner steel plates were introduced during the 1957 stabilisation campaign. After long-term exposure to moisture, some of these steel components had corroded and expanded, causing cracking and separation of the surrounding masonry. Before intervention, each corner masonry column was measured and photographically documented.



Where the locally exposed corner steel plates showed only mild corrosion, loose corrosion products and dust were removed. Two coats of anti-corrosion coating were then applied, after which the corner masonry columns were rebuilt using custom-made bricks.



Mild surface corrosion before treatment



Removal of loose surface corrosion products



Application of two coats of anti-corrosion coating after rust removal



Rebuilding of a corner masonry column containing a mildly corroded steel plate

During reconstruction of the corner masonry columns, steel wire mesh approximately 300 mm wide was installed on both sides of the steel plate to control cracking at the steel–masonry interface. Two tie bars were welded at approximately 500 mm vertical intervals to improve the connection between the steel plate and the surrounding masonry.



Steel wire mesh installed on both sides of the steel plate



Two tie bars welded at approximately 500 mm vertical intervals

Severely corroded corner steel plates were exposed and cleaned, and their original dimensions were recorded. A new steel plate of matching dimensions was welded to the retained plate, followed by the application of an anti-corrosion coating.



Severe corrosion of the steel plate within corner masonry column No. 5 at the fourth level



A new steel plate of matching dimensions welded to the retained original plate

Two coats of anti-corrosion coating were applied to the newly welded steel plate. The surrounding masonry was then rebuilt using the same procedure adopted for the other corner masonry columns. Tie bars and steel wire mesh were incorporated to improve the steel–masonry connection, control recurrent cracking, and reduce rainwater penetration through the repaired interface.



Original condition of corner masonry column No. 5 at the fourth level



Rebuilt corner masonry column No. 5 at the fourth level

Steel dowels inserted into the masonry joints of the bracket-set zone



Two holes with a depth greater than 40 mm were drilled into the masonry joints. Structural anchoring adhesive was injected into each hole, after which steel dowels were inserted and concealed with compatible repair mortar. Two dowels were installed for each relevant masonry unit.



Masonry repointing works

Open and deteriorated masonry joints allowed rainwater to penetrate the pagoda body and wash out portions of the internal earthen infill, potentially accelerating material deterioration. Following the on-site technical assessment, comprehensive masonry repointing was undertaken across the affected external surfaces.



Before repointing



After repointing

Masonry repointing procedure

Loose particles, deteriorated material, and surface dust were first removed from the masonry joints. A handheld blower was then used to clear residual debris.

The cleaned joints were filled with compatible pointing mortar, compacted, and finished flush with the surrounding masonry surface. Excess mortar was removed before final curing.



Before

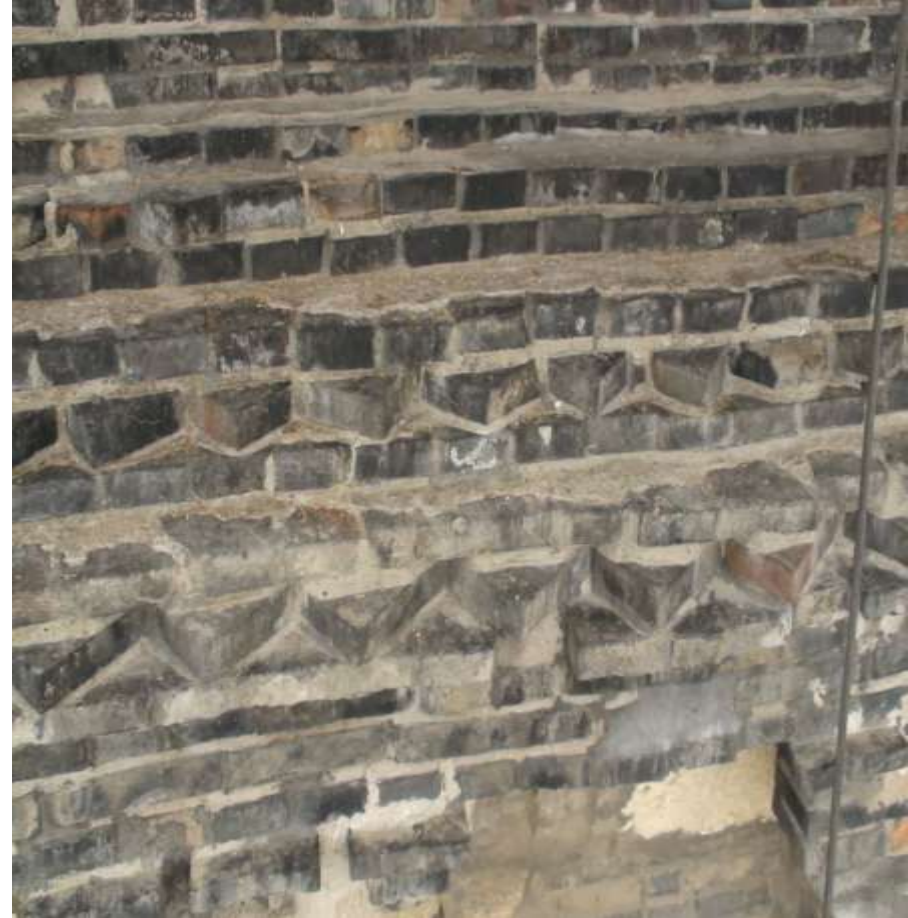


After

Comparison before and after repointing



Before



After

Arched-opening reinforcement procedure

Temporary timber supports were installed beneath the deformed arched opening. Seven grooves were cut along the masonry joints, and two reinforcing bars were inserted into each groove before being concealed with compatible repair mortar.



Existing reinforcing bars exposed as a result of corrosion
and mortar loss

Arched-opening reinforcement procedure



Seven grooves cut along the masonry joints



Reinforcing bars inserted into each groove

Comparison before and after local repair around the circumferential steel hoop



Before local repair



Crack repair around the circumferential steel hoop



After local repair



After local repair

Application of a water-repellent treatment to the external masonry surface



Application of the SNL water-repellent treatment



The treated area was protected from rainfall for seven days after application.

Drainage improvement around the pagoda



The original blue-brick paving provided inadequate surface drainage and allowed water to accumulate around the pagoda.



Replacement of the original paving with stone slabs to improve surface runoff

Overall condition of the Yunyan Temple Pagoda before and after maintenance



Before maintenance



After maintenance