*Abstract*

# Multiphysics-Enabled Digital Twin Framework for Solar Loading Thermography-Based Wood Structure Strength Prediction

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In this study, we employ solar loading infrared thermography to non-invasively assess the internal defects and degradation of the millennium-old composite wooden columns at Baoguo Temple [1,2,3]. As one of China's best-preserved heritage timber structures (See Figure 1.), the temple's mortise-and-tenon construction and fine inter-joint gaps are highly susceptible to moisture ingress and biological decay, leading to soft rot and micro-cracks. Traditional invasive probes are time-consuming and risk surface damage. By harnessing diurnal solar loading, we record surface thermal responses at multiple time-points from sunrise to noon using a mid-wave infrared camera [4], capturing subsurface anomalies—such as fissures, insect galleries, and decay—manifested as thermal contrasts [5,6].

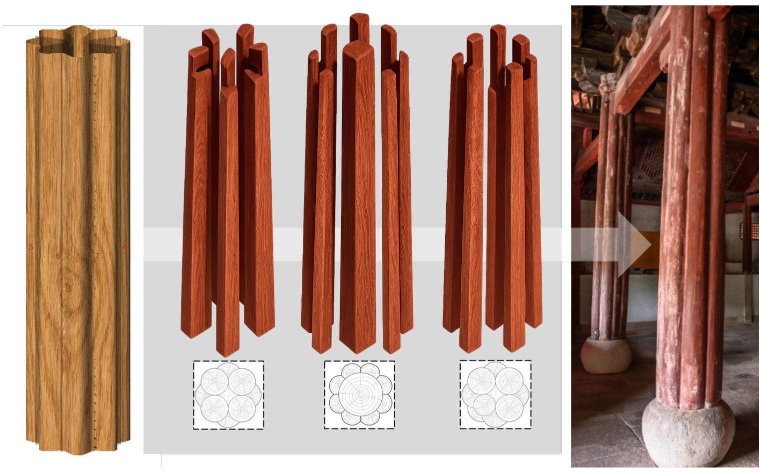

**Figure 1.** Setup of Baoguo Temple's columns

Thermal images are preprocessed by background subtraction and temporal differential filtering to enhance weak anomaly signals. A segmentation algorithm automatically delineates thermal anomaly contours, which are then spatially registered onto a high-resolution 3D scan of the composite column (See Figure 2.).

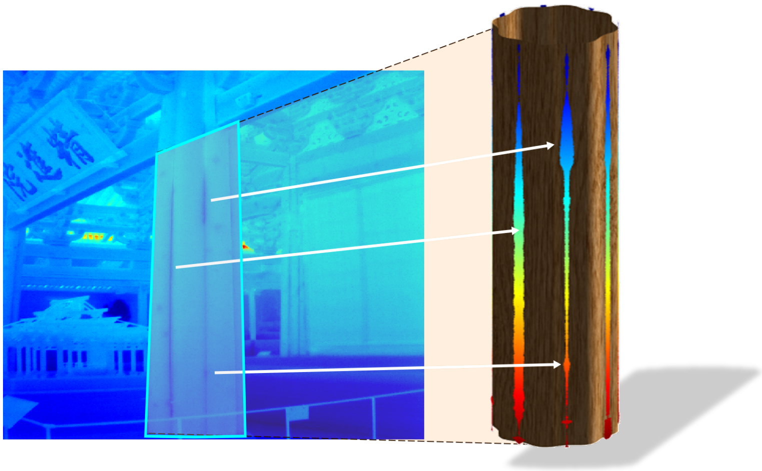

**Figure 2.** 3D model of the column assembly situation.

Integrating environmental monitoring data, we incorporate real - time wind speed, relative humidity, and precipitation into the evaluation workflow. Wind loads [7], derived from computational fluid dynamics simulations, are applied over the column's composite surfaces, while moisture ingress under humidity and rainfall is modeled via diffusion equations to adjust local mechanical properties[8]. This Multiphysics coupling reveals the stress concentration and deformation evolution within defect zones under realistic climatic conditions [9].

Finally, leveraging the material degradation map from thermography and the Multiphysics loading scenario, we develop a transient finite-element model that yields 3D stress and displacement fields. By benchmarking simulated stresses against timber bending and compressive strength limits, we compute safety factors and flag high-risk composite joints and decay zones for prioritized intervention [10]. This non-destructive workflow obviates manual probing, enabling rapid on-site defect detection and preliminary structural health assessment, thus supporting informed conservation strategies [11,12].

This work pioneers the integration of solar loading infrared thermography, and Multiphysics transient numerical simulation into a cohesive "detection–modeling–evaluation" workflow, offering a replicable, non-contact methodology for structural health monitoring and risk assessment of heritage timber architecture. Initially, diurnal solar excitation generates surface thermal gradients, recorded by a mid-wave infrared camera to achieve high-resolution imaging of subsurface anomalies such as fissures, soft rot, and insect galleries within the millennium-old composite columns of Baoguo Temple. Subsequently, accurate 3D scanning collects the geometric data of the column assemblies, which are co-registered with thermal imagery to establish a spatially consistent dataset for numerical analysis.

By coupling environmental monitoring (wind speed, relative humidity, and precipitation) with imposed mechanical loads (bending moments and axial pressures), the Multiphysics simulation accounts for the dynamic influence of climatic conditions and service loads on timber properties. Wind loads, derived from computational fluid dynamics, adhere to the column surfaces, while moisture diffusion models dynamically adjust local moisture content and elastic modulus. Finally, the material degradation map extracted from thermography feeds into a transient finite element model that outputs real-time 3D stress and displacement fields (See Figure 3.).

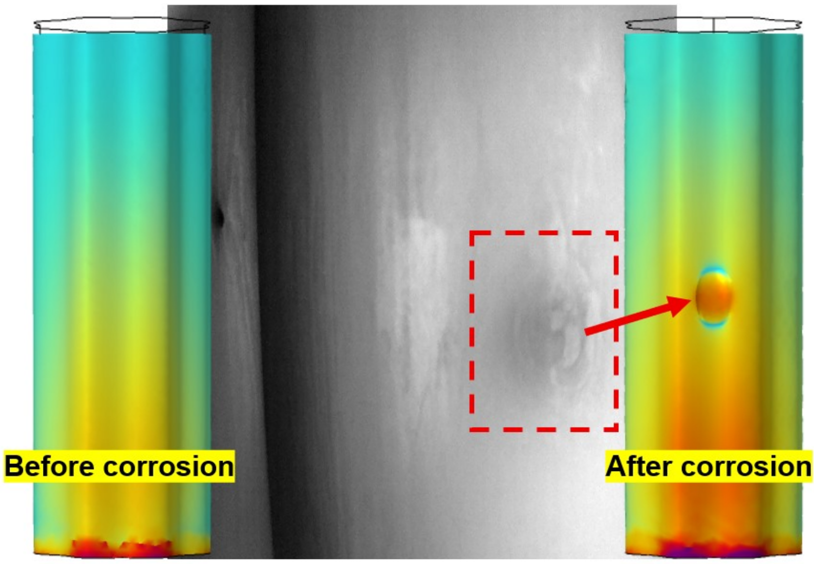


**Figure 3.** An example of the impact of soft rot on the strain field of three-dimensional models

Safety factors are computed by benchmarking simulated stresses against timber bending and compressive strength limits, and high-risk zones are flagged for prioritized intervention. This non-destructive workflow eliminates the need for invasive probing, balancing detection efficiency with preservation safety, and enables rapid on-site workflows for “defect detection–risk quantification–maintenance planning.”

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**Conflicts of Interest:** The authors declare no conflicts of interest

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