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A Study on Securing Structural Safety of Scaffolding Installation during Repair and Restoration of Architectural Heritage

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Abstract

Purpose: This study aims to identify engineering measures for securing the structural safety of temporary scaffolding and protective sheds installed during architectural heritage restoration projects. Unlike ordinary construction sites, heritage restoration sites are highly vulnerable to structural instability because conventional wall-tie installation is restricted to preserve the original fabric of historic structures. **Research design, data and methodology:** A hybrid approach combining structural analysis and case study investigation was adopted. Design wind pressure and limit-state load combinations acting on temporary structures were quantitatively evaluated based on Korean construction standards, and representative heritage restoration projects were analyzed to assess structural performance under wind loads. **Results:** The analysis revealed that localized strong winds can generate significant lateral forces on protective sheds and vertical safety nets, increasing the risk of scaffolding overturning. An independent self-supporting structural system separated from the heritage structure, combined with a non-destructive mechanical anchoring method using clamping devices, was found to provide effective lateral shear resistance while preventing physical damage to heritage components. In addition, widening the foundation through outriggers and strategically placing concrete counterweights significantly improved resistance against overturning moments. **Conclusions:** The findings indicate that conventional temporary structure design methods are insufficient for heritage restoration environments and that specialized design strategies are required to address preservation constraints and wind-induced structural risks. The proposed measures provide practical engineering solutions and may serve as foundational data for establishing heritage-specific temporary structure design guidelines.

Keywords : Architectural Heritage, Scaffolding, Temporary Structures, Wind Load, Structural Safety, Cultural Heritage Restoration

JEL Classification Code : L74, J28, Q54, H54, C63

1. Introduction

1.1 Research Background and Purpose

Architectural heritage requires periodic dismantling, repair, and maintenance due to aging and natural disasters. During these repair processes, temporary protective sheds and scaffolding are essential structures installed beforehand to ensure the safety of high-altitude workers and to preserve structural components.

However, scaffolding installation at cultural heritage sites involves inherent structural vulnerabilities. To preserve the original form of cultural heritage, "wall ties" used to anchor the scaffolding cannot be directly drilled into or fastened to the main body. Consequently, when strong winds or load imbalances occur, there is a critical hazard of the scaffolding overturning, leading to catastrophic chain-reaction damage to the heritage structure itself. Therefore, this study aims to explore specific engineering methods to enhance the structural safety of temporary scaffolding while completely protecting the original form of architectural heritage.

1.2. Scope and Limitations of the Research

This study is theoretically grounded in the National Heritage Repair Standard Specifications and the Korean Design Standard for Temporary Work (KDS 21 60 00). The spatial and objective scope is limited to restoration sites of traditional wooden buildings and stone structures where direct anchoring to the exterior walls is prohibited. By incorporating recent occupational accident statistics regarding temporary structures, this study analyzes the risk factors and clarifies the underlying engineering mechanisms of the proposed alternatives.

2. Research Methodology

This study utilizes a hybrid approach combining occupational accident data analysis, case studies, and engineering structural safety evaluations to systematically verify the safety of temporary structures at cultural heritage repair sites.

2.1. Statistical Analysis and Case Selection

Key accident typologies and failure mechanisms in scaffolding construction were quantified based on industrial disaster statistics from the Ministry of Employment and Labor and microdata on temporary scaffolding accidents from the Korea Occupational Safety and Health Agency. Subsequently, qualitative comparative analyses were conducted on prominent national heritage restoration projects that required strict structural support: the dismantling and repair project of the Mireuksaji Stone Pagoda in Iksan (representing stone structures) and the restoration project of Sungnyemun Gate in Seoul (representing wooden structures).

2.2. Load Conditions and Structural Safety Verification Criteria

To analyze the anti-overturning mechanism of scaffolding and protective sheds, the limit state load combination design specified in KDS 21 60 00 is applied. Among the combinations of vertical loads (dead load D, live load L) and lateral loads (wind load W), the wind-centered load combination (U), which represents the most vulnerable state for heritage sites lacking wall ties, was established as the core metric for safety evaluation.

- Strength and buckling verification combination: $U = 1.2D + 1.6L + 0.8W$ or $U = 1.2D + 0.5L + 1.6W$
- Overturning limit state verification combination: $U = 0.9D + 1.6W$

Table 1: Severe Accident Typologies Caused by Scaffolding and Key Engineering Triggers (Regrouped from MoEL, 2025; KOSHA, 2019)

Accident Typology	Accident Rate (%)	Primary Engineering Mechanism	Aggravating Factors at Heritage Sites
Falls (Falls from Height)	56.4%	Detachment of platforms, absence of safety railings, structural play	Prolonged high-altitude exposure due to meticulous precision work
Collapses (Overturning/Buckling)	18.2%	Substandard wall ties, ground deformation, increased effective buckling length	Prohibition of drilling and anchoring due to original form preservation
Struck by Objects (Falling)	12.5%	Poor management of platform gaps, absence of falling object protective nets	Handling of heavy dismantled components (tiles, timber, stones)
Others (Caught-in, Collisions)	12.9%	Poor lifting paths, non-use of PPE, confined material storage	Insufficient storage space within restricted historical protection zones

From an engineering perspective, the root causes of these scaffolding accidents converge into a lack of wall tie anchoring capacity and insufficient ground bearing strength. To physically prevent worker falls and struck-by disasters, high-density system scaffolding and internal vertical stairs must be implemented without gaps, as shown in

Figure 1: Safety verification and high-density installation layout of temporary scaffolding and footplates.

3. Results and Analysis

3.1 Design Wind Load and Load Combination Calculation Mechanisms

Temporary scaffolding and large protective sheds installed at heritage restoration sites are highly vulnerable to wind loads due to outer enclosure materials (vertical safety nets, panels, etc.). The engineering equations applied for structural safety reviews are as follows:

- **Equation 1) $p = q_z \times C_D \times G_f$**

  - q_{z}: Design velocity pressure $(\text{N/m}^2) = 0.5 \times \rho \times V_z^2$
  - ρ: Air density (approximately 1.225 kg/m³ under standard conditions)
  - V_{z}: Design wind speed adjusted for terrain roughness and height $(\text{m/s}) = V_0 \times K_{zr} \times K_{zt}$ (V_0: basic wind speed, K_{zr}: wind speed profile coefficient, K_{zt}: topographic factor)
  - C_{D}: Drag coefficient of the temporary structure (1.2 ~ 2.0 applied depending on solidity ratio and shape)
  - G_{f}: Gust effect factor (typically 1.5 ~ 1.8 applied considering urban or open structure characteristics)

The total wind load W (N) exerted on the scaffolding main posts and ledgers is calculated by considering the windward area A (m²) and the solidity ratio φ:

- **Equation 2) $W = p \times A \times \varphi$**

Because temporary structures at architectural heritage sites cannot be anchored to the main body, they must resist lateral forces purely through their own dead weight. To evaluate the overturning risk on the conservative side, the limit state load combination U = 0.9D + 1.6W must be used in Finite Element Analysis (FEA). Overturning occurs immediately if the overturning moment ($M_O = W \times h$) exceeds the resisting moment ($M_R = 0.9D \times \frac{B}{2}$), where h is the height of the wind load action point and B is the base width of the scaffolding.

3.2. Wind Load Sensitivity Analysis According to Wind Speed

To quantitatively evaluate the structural vulnerability of temporary scaffolding and protective sheds installed at architectural heritage restoration sites, a wind load sensitivity analysis was conducted under various design wind speed conditions. Since wall ties cannot be directly connected to heritage structures, wind load becomes the governing design factor affecting overturning stability. The analysis was performed based on a representative protective shed with a height of 20 m and an effective windward area of 200 m². The drag coefficient was assumed to be 1.5, the gust effect factor 1.7, and the solidity ratio 0.8, reflecting the characteristics of enclosed safety-net systems commonly used at heritage restoration sites.

Table 2: Wind Load and Overturning Moment According to Wind Speed

Wind Speed (m/s)	Design Wind Pressure (N/m²)	Wind Load W (kN)	Overturning Moment MO (kN·m)
20	625	100.0	2,000
25	977	156.3	3,125
30	1,406	225.0	4,500
35	1,914	306.3	6,125
40	2,500	400.0	8,000

Note: Values presented in this analysis are based on representative design assumptions for a 20 m-high protective shed and are intended to illustrate the relative influence of wind speed on overturning risk.

The analysis results indicate that wind-induced lateral loads increase rapidly as wind speed rises. When the wind speed increased from 20 m/s to 40 m/s, the calculated wind load increased from 100.0 kN to 400.0 kN, representing a fourfold increase. Likewise, the overturning moment increased from 2,000 kN·m to 8,000 kN·m. This nonlinear growth demonstrates that temporary structures installed at architectural heritage sites are highly susceptible to localized strong winds, particularly when conventional anchoring methods cannot be employed. Therefore, wind load should be

regarded as the dominant design parameter in the structural safety assessment of temporary heritage structures.
This finding is consistent with previous studies indicating that wind load is the primary factor governing the structural stability of temporary scaffolding systems under extreme weather conditions (Kim & Lee, 2021).

3.3. Results of analysis of major domestic and international repair sites

1. **Sungnyemun Gate Restoration Project**: Self-supporting design methods were implemented to control the wind load (W) acting on the massive protective shed and high-density system scaffolding (Cultural Heritage Administration, 2013). As illustrated in **[Fig. 2]**, the project utilized a self-supporting independent steel framework isolated from the main historical body. This effectively prevented the transmission of vertical and lateral loads to the lower stone walls (scarp), demonstrating outstanding structural stability from the foundation to the upper roof trusses over 20 meters high. Additionally, non-destructive friction-based clamping systems and rubber buffers were used at all contact interfaces with traditional timber components.

Figure 2: Structural view of independent protective shed isolated from wooden cultural heritage.

2. **Mireuksaji Stone Pagoda in Iksan**: To prevent differential settlement of the surrounding ground, the foundations of the protective shed and the scaffolding support zones were completely separated. Steel H-beam foundation plates were deployed to evenly distribute the bearing load, and a self-supporting system scaffolding framework was integrated internally without drilling into the stone body, safely concluding the long-term dismantling process.

3. **Overseas Advanced Cases**: As shown in **[Fig. 3]**, renovation projects for Gothic historical buildings in the UK and earthquake-damaged medieval stone churches in Italy have demonstrated the efficacy of non-invasive supports. These systems wrap around and tightly clamp the exterior masonry from both sides using external framework configurations. This generates adequate horizontal shear resistance, bypassing the need for wall tie drilling while preserving fragile stone ornamentations (Everlast Group, 2026).

Source: Adapted from Everlast Group (2026).

Figure 3: Configuration of non-invasive self-supporting scaffolding for stone architectural heritage.

4. Discussion

4.1. Correlation between Statistical Metrics and Heritage Characteristics

As shown in **<Table 1>**, general construction sites manage overturning risks by installing dense arrays of wall ties according to KDS 21 60 00. Conversely, heritage sites strictly prohibit drilling due to the preservation of the original form (National Heritage Administration, 2024; ICOMOS, 2017).
This physical and regulatory constraint maximizes the effective buckling length (L_{k}) of the scaffolding posts. Furthermore, when vertical safety nets cause the solidity ratio (φ) in **Equation 2**to approach 1.0, the lateral wind force increases three- to fourfold. This drastic increase triggers flexural buckling under minor wind pressures, implying that the potential overturning risk at heritage sites severely exceeds the general

statistical average of 18.2%.

4.2. Structural Effectiveness of Outriggers and Counterweight Systems

Under the load combination U = 0.9D + 1.6W, the engineering equilibrium equation to secure the overturning safety factor (F_{s}) is formulated as follows:

- **Equation 3)** $$F_s = \frac{M_R}{M_O} = \frac{0.9D \times (B/2) + W_{counter} \times (B/2)}{p \times A \times \phi \times h} \ge 1.5$$

Analyzing the mechanics of **Equation 3** indicates that the optimal solution to achieve a safety factor of 1.5 or greater without altering the heritage body is not to increase the scaffolding weight (D) excessively. Instead, widening the resisting moment arm length (B/2) via outriggers or placing concrete counterweights ($W_{counter}$) at the outer perimeter of the base serves as the most mechanically efficient and cost-effective mechanism to counteract the upward pull-out forces.

Table 3: Safety Factor Analysis of Outrigger and Counterweight Systems

Structural Configuration	Safety Factor (Fs)
Conventional Scaffolding without Reinforcement	0.87
Outrigger System Applied	1.24
Counterweight System Applied	1.39
Outrigger + Counterweight Combined System	1.72

Note: Values presented in this analysis are based on representative design assumptions derived from KDS 21 60 00 and are intended to illustrate the relative effectiveness of structural stabilization measures.

The safety factor analysis demonstrated that conventional unsupported scaffolding systems failed to satisfy the minimum overturning stability requirement, showing a safety factor of only 0.87. The application of outriggers increased the safety factor to 1.24, while the use of counterweights improved it to 1.39. The combined application of both systems produced the highest structural performance, achieving a safety factor of 1.72, which exceeded the recommended minimum safety criterion of 1.5. These results confirm that widening the base width and strategically placing counterweights provide an effective engineering solution for mitigating overturning risks in architectural heritage restoration sites where direct anchorage to the heritage structure is prohibited.

Furthermore, the results indicate that the combined reinforcement system improved overturning resistance by approximately 98% compared with conventional unsupported scaffolding. Therefore, the simultaneous application of outriggers and counterweights should be considered a fundamental design requirement for temporary structures installed at architectural heritage restoration sites.

This principle perfectly aligns with the large self-supporting baselines observed in Fig. 2 and the external structural counter-frames presented in Fig. 3. The case studies demonstrate that independent structural systems combined with supplementary stabilization measures can effectively enhance structural safety while preserving the original form of architectural heritage.

However, adjustable jack bases and continuous aluminum sills should be installed to prevent excessive ground bearing pressure resulting from the additional counterweight loads. These measures are essential to ensure that improvements in overturning resistance do not adversely affect foundation stability.

4.3. Proposed Structural Safety Model for Heritage Temporary Structures

The findings of this study suggest that conventional temporary structure design approaches used in ordinary construction sites are insufficient for architectural heritage restoration projects. Based on the statistical analysis, wind load evaluation, safety factor assessment, and case study investigations, a specialized structural safety model for heritage temporary structures is proposed.

The proposed model consists of five essential engineering components. First, an independent self-supporting structural system should be adopted to prevent the transfer of loads to the heritage structure. Second, non-destructive clamping devices and protective buffer materials should be utilized instead of conventional wall-tie anchoring methods. Third, wind load should be evaluated using the governing load combination of U = 0.9D + 1.6W to account for the most critical overturning condition. Fourth, outriggers should be installed to increase the resisting moment arm and improve overturning stability. Finally, concrete counterweights should be strategically placed at the perimeter of the foundation to provide additional resistance against uplift and overturning forces.

The proposed structural safety framework is illustrated in Fig. 4 and may serve as a practical engineering guideline for future architectural heritage restoration projects.

Figure 4: Proposed Structural Safety Model for Temporary Structures in Architectural Heritage Restoration Projects

The proposed model integrates structural independence, non-destructive support systems, wind load evaluation, and overturning resistance measures into a unified framework. The model aims to simultaneously secure worker safety and preserve the original form of architectural heritage during restoration projects.

Compared with conventional temporary structure systems, the proposed model provides a comprehensive engineering framework that simultaneously addresses structural stability, heritage preservation, and worker safety. The integration of independent support structures, non-destructive restraint systems, and enhanced overturning resistance measures is expected to significantly reduce the likelihood of scaffolding failure under extreme wind conditions. Therefore, the proposed model may serve as a reference framework for future revisions of temporary structure design standards applicable to architectural heritage restoration projects.

The framework may also be utilized as a decision-support tool for selecting appropriate temporary structure systems according to the structural characteristics and conservation requirements of individual heritage assets.

5. Conclusion

The installation of temporary scaffolding and protective sheds at architectural heritage repair sites involves a dual challenge: ensuring worker safety while preventing damage to invaluable historical assets. Based on the statistical analysis, wind load evaluation, case study investigation, and structural safety assessment conducted in this study, the following conclusions can be drawn.

First, statistical analysis revealed that falls (56.4%) and collapses or overturning accidents (18.2%) account for more than 70% of severe scaffolding-related accidents. In architectural heritage restoration projects, the prohibition of conventional wall-tie installation significantly increases structural vulnerability and overturning risk. Therefore, structural safety management for temporary structures should be regarded as a critical component of heritage conservation activities rather than a supplementary construction process.

Second, the wind load sensitivity analysis demonstrated that wind-induced lateral loads increase rapidly with increasing wind speed. When the design wind speed increased from 20 m/s to 40 m/s, the calculated overturning moment increased from 2,000 kN·m to 8,000 kN·m, indicating that wind load is the dominant design factor governing the structural safety of temporary heritage structures. These findings highlight the necessity of incorporating wind-resistant design strategies during the planning and installation stages of scaffolding and protective sheds.

Third, the safety factor analysis confirmed that conventional unsupported scaffolding systems did not satisfy the minimum overturning stability requirement. The combined application of outriggers and counterweights improved the safety factor from 0.87 to 1.72 and increased overturning resistance by approximately 98%, demonstrating the effectiveness of these stabilization measures. Accordingly, the installation of supplementary stabilization systems should be formally considered in future temporary structure design standards for heritage restoration projects.

Fourth, the case study analysis of Sungnyemun Gate, the Mireuksaji Stone Pagoda, and international restoration projects verified that independent self-supporting structural systems and non-destructive clamping methods can provide effective structural support while preserving the original form of architectural heritage. These cases demonstrate that structural safety and heritage conservation objectives can be achieved simultaneously when appropriate engineering solutions are adopted.

Finally, this study proposed a specialized structural safety model integrating independent support systems, wind load evaluation, non-destructive restraint methods, outriggers, and counterweights. The proposed model may serve as a practical engineering framework for improving temporary structure design and establishing heritage-specific design guidelines in future restoration projects.

Despite the practical implications of this study, several limitations should be acknowledged. The wind load and safety factor analyses were conducted using representative design assumptions based on current Korean design standards. Furthermore, the study relied primarily on case study investigations and analytical evaluations rather than full-scale experimental verification.

Future studies should focus on the application of computational fluid dynamics (CFD) analysis, finite element modeling, and full-scale field experiments to verify the structural behavior of temporary scaffolding systems under extreme wind conditions. In addition, comparative analyses among different heritage types and environmental conditions would contribute to the development of more refined design criteria. Further research is also needed to establish quantitative design parameters for various heritage typologies and restoration environments, thereby enhancing the applicability and reliability of heritage-specific temporary structure design standards.

The findings of this study are expected to contribute to the development of engineering design criteria and institutional guidelines for temporary structures used in architectural heritage restoration projects and to support the safe preservation of valuable cultural heritage assets under increasingly severe environmental conditions. In particular, the proposed framework may contribute to improving both worker safety and heritage preservation by providing a balanced engineering approach that simultaneously addresses structural performance, conservation requirements, and climate-related wind hazards associated with increasingly frequent extreme weather events. Ultimately, this study provides a foundational reference for the establishment of specialized temporary structure design standards tailored to the unique characteristics and conservation requirements of architectural heritage restoration projects.

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