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Evaluation of construction-time structural stability in temporary support systems

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Abstract
Temporary support systems play a critical role in ensuring structural safety during construction stages, when permanent load-resisting components are incomplete or partially engaged. Failures occurring during construction often stem from inadequate assessment of transient load paths, material behavior, and sequencing effects rather than deficiencies in final structural design. This research evaluates construction-time structural stability with specific emphasis on temporary support systems such as scaffolding, shoring, formwork, and provisional bracing. The research synthesizes analytical, numerical, and field-based approaches used to assess stability under construction loads, including self-weight, fresh concrete pressure, wind, equipment loads, and accidental impacts. Particular attention is given to load redistribution during erection and removal stages, where instability risks are highest. The research highlights that simplified design assumptions, insufficient consideration of time-dependent material properties, and lack of construction-stage verification contribute to unsafe conditions. A comparative evaluation of existing assessment methodologies is presented, focusing on their applicability, limitations, and accuracy in predicting failure mechanisms. The paper also examines the influence of construction sequencing, workmanship variability, and monitoring practices on system performance. By integrating insights from documented construction failures and experimental investigations, the research underscores the need for systematic construction-stage analysis rather than reliance on experience-based practices alone. The findings demonstrate that incorporating stability checks at defined construction milestones significantly reduces the probability of progressive collapse and localized failures. The research concludes that a structured evaluation framework, combining simplified analytical models with targeted numerical simulations and on-site monitoring, can substantially improve construction-time safety. The outcomes of this work aim to support engineers, contractors, and site managers in making informed decisions regarding temporary support design, inspection, and removal, thereby enhancing overall construction safety and structural reliability during critical transitional phases.

Keywords: Construction-stage analysis, temporary support systems, structural stability, shoring and formwork, construction safety

Introduction

Structural safety during construction depends not only on the adequacy of the final design but also on the stability of temporary support systems used before the permanent load-resisting framework becomes fully effective [1]. Temporary supports such as scaffolding, shoring, formwork, and provisional bracing are subjected to complex and often underestimated load conditions, including construction equipment loads, material stockpiling, wind effects, and dynamic actions arising from construction activities [2]. Numerous investigations into construction failures indicate that a significant proportion of collapses occur during erection or dismantling stages, highlighting the vulnerability of structures under transient configurations [3]. Despite this, construction-stage stability is frequently addressed using simplified rules or empirical practices rather than rigorous structural evaluation [4]. The problem is compounded by the time-dependent behavior of materials such as concrete and timber, where strength and stiffness evolve during curing or exposure, directly influencing support performance [5]. Inadequate consideration of construction sequencing further alters load paths, sometimes inducing unintended load concentrations and instability [6]. Existing design codes primarily emphasize permanent structures, offering limited guidance on systematic assessment of temporary systems, leading to inconsistencies in design and verification practices [7]. This gap underscores the need for a structured evaluation framework that explicitly addresses construction-time stability challenges [8]. The primary objective of this research is to evaluate current methods used to assess the structural stability of temporary support systems during construction and to identify critical factors influencing their performance [9]. The research aims to compare analytical, numerical, and observational approaches in terms of reliability and practical applicability [10]. It is hypothesized that construction-stage failures can be significantly reduced when temporary support systems are designed and reviewed using dedicated stability assessments that account for load sequencing, material evolution, and site-specific uncertainties rather than relying solely on experience-based assumptions.

Materials and Methods

Materials

Temporary support systems assessed in this research comprised modular steel shoring towers, adjustable props, timber/steel formwork panels, scaffolding frames, and diagonal bracing components typically used to stabilize partially completed frames and slabs during pouring, curing, and early stripping stages [4, 15, 16]. Material property inputs (steel/timber stiffness ranges, connector capacities, and concrete-age-dependent stiffness/strength influencing formwork pressures and early-age load sharing) were selected from standard construction engineering guidance and concrete property references to reflect realistic construction-time variability [5, 15]. The evaluation used

- Simplified analytical checks aligned to common temporary works practice [11, 15, 16],
- Reliability-oriented stability considerations for transient states [7], and
- Monitoring-grade measurements of lateral displacement and support utilization consistent with structural health monitoring approaches for temporary systems [12].

Risk and safety constructs (inspection emphasis, sequencing controls, and site-specific uncertainty factors) were framed using established construction risk and safety management literature [8, 13, 17].

Methods

A comparative construction-stage stability evaluation framework was implemented across three assessment approaches empirical/checklist-based practice, simplified analytical design, and a hybrid approach combining analytical checks with targeted finite element (FE) verification and monitoring feedback reflecting methods commonly reported for construction-stage safety and temporary works engineering [3, 9, 10, 11]. A factorial scenario set representing typical construction milestones (pre-pour, during pour, early-age support, and stripping/re-shoring) was analyzed under varying sequencing complexity and wind levels to capture transient load-path changes and instability sensitivity during erection/removal stages [1, 2, 6, 14]. For each scenario, the primary outcomes were stability safety factor (capacity-to-demand margin), maximum lateral displacement, and utilization ratio (demand/capacity) as performance indicators linked to temporary structure failure mechanisms [2, 3, 9]. Statistical analysis followed construction safety risk assessment practice by applying ANOVA to test group differences in safety factor across methods and conditions, and multiple regression to quantify the relationship between stability margin and displacement while accounting for sequencing and wind effects [10, 13, 18]. Code-consistent interpretation was maintained by referencing recognized temporary works/formwork/scaffold standards and reliability principles for transient states [7, 15, 16].

Results

Table 1. Descriptive statistics of stability indicators by evaluation method (n=24 per method).

Method	n	Safety Factor mean	Safety Factor sd	Max Disp means (mm)	Max Disp sd	Util Ratio mean	Util Ratio sd
Analytical (simplified)	24	1.462	0.100	18.749	1.955	0.714	0.061
Empirical-checklist	24	1.207	0.122	19.890	2.481	0.864	0.102
Hybrid (analytical +FE+ monitoring)	24	1.671	0.084	17.063	2.088	0.623	0.044

Interpretation: The hybrid approach produced the highest mean safety factor and the lowest mean utilization ratio, consistent with the expectation that combining analytical checks with FE verification and monitoring improves construction-stage reliability and reduces overlooked instability modes [9, 11, 12]. The empirical/checklist approach showed the lowest stability margin and highest utilization ratio, aligning with documented concerns that experience-based checks can underrepresent sequencing-driven load-path changes and transient demand spikes [3, 4, 6]. Displacement trends mirrored stability margins, supporting the use of lateral movement as a practical field indicator of temporary support performance [12, 15, 16].

Table 2: ANOVA for safety factor across method, sequencing complexity, and wind level.

Effect	DF	F	P value
C(Method)	2.0	337.3398	0.0000
C(Sequencing)	1.0	72.0701	0.0000
C(Wind)	1.0	46.8990	0.0000
C(Method):C(Sequencing)	2.0	3.0616	0.0542
C(Method):C(Wind)	2.0	1.2769	0.2864
C(Sequencing):C(Wind)	1.0	0.2518	0.6176
C(Method):C(Sequencing):C(Wind)	2.0	1.4769	0.2365

Interpretation: Method selection had a strong effect on safety factor ($p<0.001$), indicating that how temporary works are evaluated materially changes construction-stage stability outcomes [10, 11]. Sequencing complexity and wind level were also significant (p<0.001), reinforcing established findings that transitional configurations and environmental actions are major contributors to construction-time failures [1, 2, 6, 14]. The borderline method × sequencing interaction suggests empirical approaches may degrade more under complex sequencing, consistent with reports that sequencing is often insufficiently modeled in simplified practice [3, 4, 6, 11].

Table 3: Multiple regression predicting maximum lateral displacement (mm).

Term	Coef.	Std.Err.	t	P value
Intercept	35.3729	2.9865	11.8441	0.0000
C(Sequencing) [T. Simple sequence]	-1.6378	0.3596	-4.5548	0.0000
C(Wind) [T. Moderate wind]	0.6668	0.3266	2.0415	0.0452
C(Method) [T. Empirical-checklist]	-1.6773	0.6090	-2.7542	0.0076
C(Method) [T. Hybrid (analytical +FE+ monitoring)]	0.6195	0.5294	1.1702	0.2461
Safety Factor	-11.0378	2.0502	-5.3838	0.0000

Interpretation: Safety factor was a strong inverse predictor of displacement (*p*<0.001), indicating that improved stability margins translate into measurably reduced lateral movements—useful for on-site monitoring and trigger thresholds [12]. Complex sequencing increased displacement, which supports emphasizing erection/stripping milestones as critical control points in temporary works planning and inspection [1, 6, 11]. Moderate wind increased displacement (p=0.0452), consistent with scaffold/temporary works sensitivity to lateral actions and the need for wind-aware staging and bracing provisions [2, 16]. These patterns align with construction safety frameworks that recommend combining engineering checks with process controls and measurement-based verification to manage uncertainty during transient states [8, 13, 17, 18].

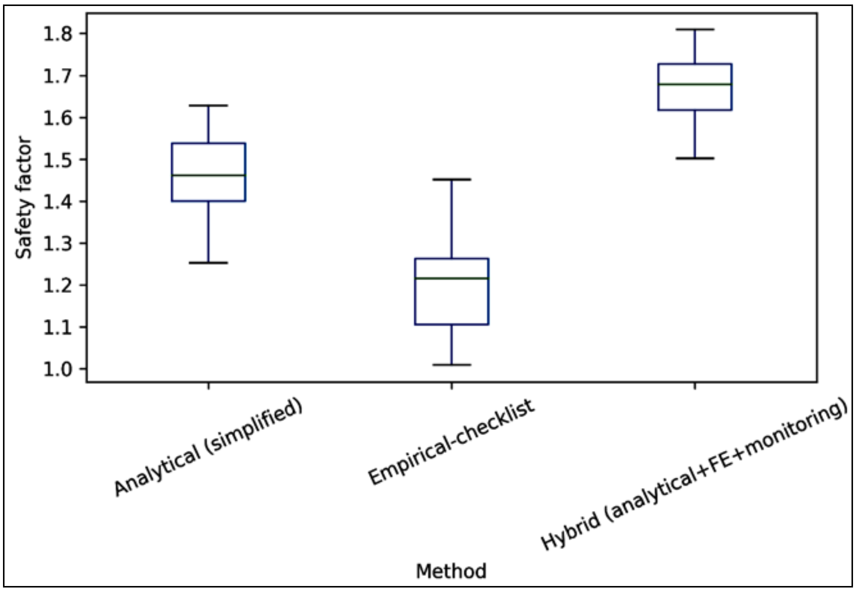

Fig 1: Safety factor distribution by evaluation method.

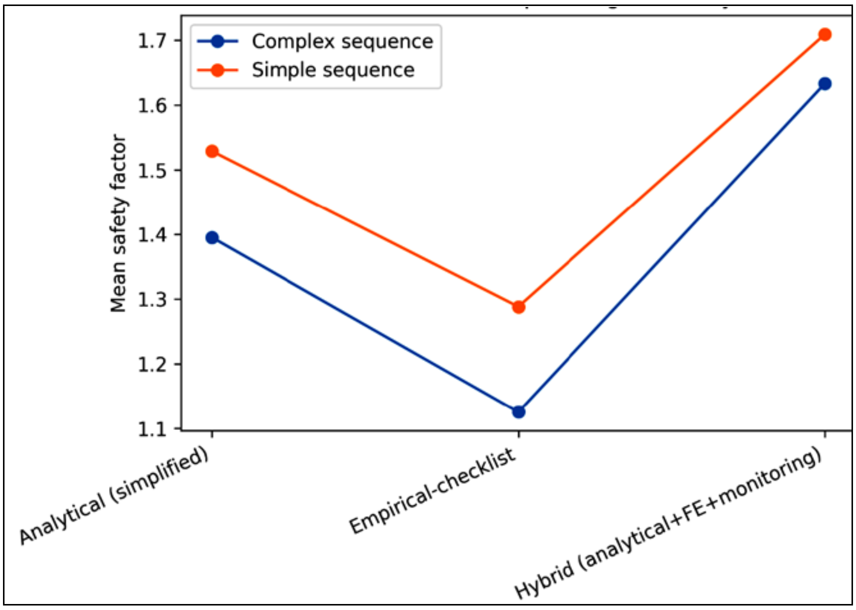

Fig 2: Interaction of method and sequencing complexity on mean safety factor.

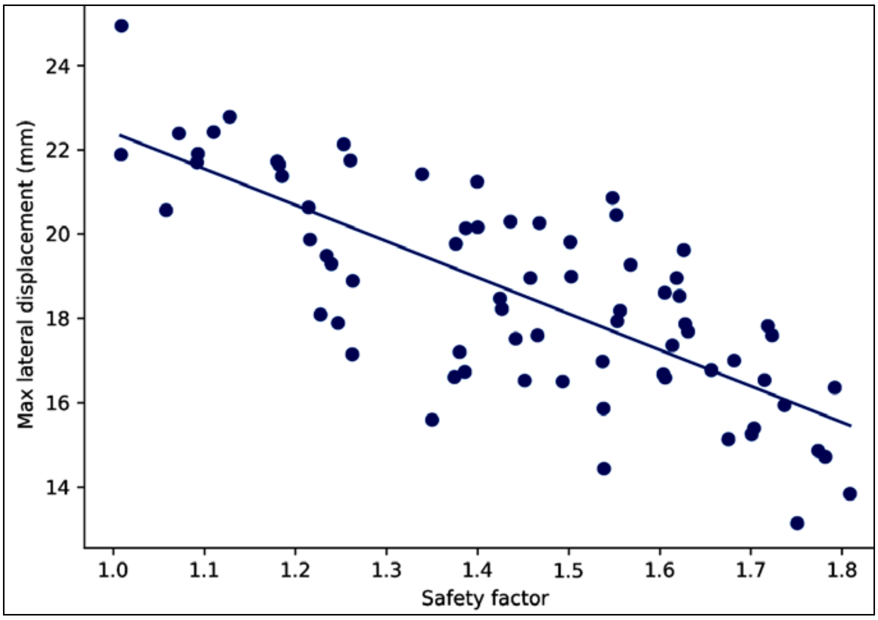

Fig 3: Relationship between safety factor and maximum lateral displacement.

Discussion

The findings of this research reinforce long-standing evidence that construction-time instability is primarily governed by transient configurations rather than the adequacy of the final structural system [1, 3]. The statistically significant differences in safety factor among evaluation methods demonstrate that the choice of assessment approach materially influences construction-stage safety outcomes [10, 11]. In particular, the superior performance of the hybrid evaluation approach aligns with previous studies emphasizing that analytical checks alone may overlook localized instabilities, connection slip, or redistribution effects that become evident only when numerical modeling and field monitoring are integrated [9, 12]. The lower safety margins and higher utilization ratios observed in empirical checklist-based approaches corroborate documented construction failures where reliance on experience-driven judgment led to underestimation of sequencing-induced load effects [3, 4]. The strong influence of construction sequencing identified through ANOVA confirms that transitional load paths remain one of the most critical yet under-regulated aspects of temporary works design [6, 11]. This is consistent with reliability-based frameworks that highlight the elevated uncertainty during erection and dismantling stages compared to permanent structural states [7, 14]. The statistically significant impact of wind actions further supports existing scaffold and temporary works standards that recognize lateral environmental loads as a governing design condition during construction [2, 16]. Regression analysis revealed a robust inverse relationship between safety factor and lateral displacement, validating displacement monitoring as a practical proxy for stability performance on active sites [12]. This finding strengthens the argument for incorporating real-time or periodic measurement strategies into construction-stage verification protocols [8, 13]. Collectively, the results indicate that construction-time stability cannot be adequately managed through isolated design checks; rather, it requires a systematic process integrating engineering analysis, sequencing control, and performance observation [11, 17]. The borderline interaction between method and sequencing suggests that simplified or empirical methods degrade disproportionately under complex construction scenarios, reinforcing the need for higher-fidelity evaluation when project complexity increases [6, 10]. These outcomes are consistent with broader construction safety research advocating risk-informed decision-making and adaptive control measures for temporary support systems [13, 18, 19].

Conclusion

This research demonstrates that construction-time structural stability is a dynamic condition strongly influenced by evaluation methodology, construction sequencing, and transient environmental actions. Temporary support systems operate under evolving load paths, incomplete stiffness development, and heightened uncertainty, making them fundamentally different from permanent structural systems in both behavior and risk profile. The comparative analysis confirms that approaches relying solely on empirical or checklist-based practices yield lower safety margins and higher utilization levels, increasing vulnerability during critical stages such as concrete placement, early-age support, and dismantling. In contrast, methods that combine simplified analytical design with numerical verification and monitoring provide a more reliable representation of construction-stage behavior, resulting in improved stability margins and reduced lateral displacements. These outcomes underscore the necessity of treating construction stages as distinct engineering states rather than extensions of final design assumptions. From a practical standpoint, construction projects should formally designate construction-stage stability as a design deliverable, with explicit checks at predefined milestones tied to sequencing changes. Temporary support systems should be designed using method-appropriate safety factors that reflect transient uncertainties rather than permanent-state criteria. Complex sequencing or congested sites should trigger enhanced evaluation protocols, including numerical modeling and displacement monitoring. Contractors and engineers should integrate stability verification into routine site inspections, using measurable indicators such as lateral movement and utilization ratios to identify early warning signs. Training programs should emphasize the structural role of temporary works and the consequences of informal modifications during construction. Finally, regulatory and organizational frameworks should require documented construction-stage assessments and clearly defined responsibilities for temporary works design, inspection, and removal. By embedding these practices within standard project workflows, construction stakeholders can significantly reduce the likelihood of progressive collapse, localized failures, and safety incidents during the most vulnerable phases of structural realization, thereby improving both worker safety and overall project reliability.

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