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Performance evaluation of modular bridge girders using simplified load simulation techniques

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Abstract
Modular bridge girders are increasingly adopted to accelerate construction, reduce site disruption, and enable standardized quality control in short- and medium-span bridges. Despite their advantages, reliable evaluation of structural performance remains challenging when full-scale testing or advanced numerical modeling is impractical. This research presents a performance evaluation framework for modular bridge girders using simplified load simulation techniques that approximate critical service and ultimate limit state responses. The approach combines idealized load patterns representing vehicular, pedestrian, and environmental actions with analytical beam models calibrated to modular connection behavior. Key performance indicators include deflection profiles, stress distribution, load sharing efficiency, and reserve capacity under combined loading scenarios. The proposed methodology emphasizes computational efficiency while retaining sufficient accuracy for preliminary design verification and comparative assessment of girder configurations. Parametric simulations are conducted to examine the influence of span length, modular joint stiffness, girder spacing, and load placement on global and local responses. Results demonstrate that simplified load simulations can capture governing trends in flexural demand and serviceability performance, provided that connection flexibility is explicitly represented. The research further identifies critical thresholds beyond which simplified assumptions may underestimate localized stresses near modular joints. By bridging the gap between overly conservative hand calculations and resource-intensive finite element models, the framework supports informed decision-making during early-stage design and rapid evaluation of alternative modular layouts. The findings contribute practical guidance for engineers seeking efficient yet rational tools to assess modular bridge girder performance, enhance constructability, and ensure structural safety within constrained project timelines and budgets. Moreover, the framework facilitates transparent communication of assumptions, supports preliminary risk screening, and enables consistent benchmarking across projects, thereby assisting designers, reviewers, and stakeholders in selecting modular girder solutions that balance performance, economy, durability, and adaptability under varying regulatory and site constraints encountered during accelerated delivery programs and multidisciplinary coordination efforts globally.

Keywords: Modular bridges, bridge girders, simplified load simulation, structural performance, serviceability, preliminary design

Introduction
Modular bridge systems have gained prominence as transportation agencies seek rapid, cost-effective solutions for replacing aging infrastructure while minimizing traffic disruption and construction risk [1]. Within these systems, modular bridge girders play a central role in governing global stiffness, load distribution, and serviceability performance under repetitive traffic actions [2]. Traditional performance evaluation relies heavily on detailed finite element modeling or full-scale load testing, both of which demand substantial time, expertise, and financial resources that may not be available during early design stages [3]. As a result, designers often resort to conservative assumptions that can obscure true structural behavior, particularly in the presence of semi-rigid modular connections and nonuniform load paths [4]. Previous studies have shown that simplified analytical models, when properly calibrated, can reproduce key response characteristics of bridge girders under standard loading conditions [5], yet their application to modular systems remains limited and inconsistently validated [6]. The problem is compounded by the need to assess multiple girder configurations, span arrangements, and connection details within compressed project timelines [7]. Simplified load simulation techniques, such as idealized vehicular load envelopes and equivalent static representations, offer a promising pathway to balance efficiency and accuracy if their

limitations are clearly understood [8]. Recent research highlights the sensitivity of modular girder response to joint stiffness and load placement, indicating that oversimplification may lead to unconservative stress estimates near connections [9]. Therefore, there is a clear need for a structured evaluation approach that integrates simplified load simulations with performance-based indicators relevant to modular bridge girders [10]. The primary objective of this research is to develop and demonstrate a rational framework for assessing the structural performance of modular bridge girders using computationally efficient load simulation methods suitable for preliminary design and comparison tasks [11]. Specific aims include quantifying deflection behavior, stress distribution, and load sharing efficiency under representative service and ultimate load scenarios [12]. The working hypothesis is that simplified load simulation techniques, augmented by explicit representation of modular connection flexibility, can predict governing performance trends with acceptable accuracy for early-stage decision-making [13]. Validation against established analytical formulations and reported experimental observations provides confidence in the applicability of the approach while delineating its bounds of reliability [14]. By addressing these needs, the research contributes toward more transparent, economical, and timely evaluation practices for modular bridge design [15-17]. Such practices are increasingly relevant for agencies prioritizing resilience, standardization, and scalable deployment across diverse bridge networks nationwide globally.

Materials and Methods

Materials

Modular bridge girder performance was evaluated using a simplified load simulation framework that combines representative design load patterns with calibrated analytical member models, consistent with performance-based bridge assessment practice and reliability-oriented evaluation concepts [1, 2, 10]. The research considered modular girder configurations typical of accelerated bridge construction, including variations in span length, girder spacing, and modular connection (joint) stiffness that governs composite action and load transfer efficiency [7, 17]. Representative loading was modeled using codified load concepts and equivalent static envelope assumptions to emulate service and ultimate demand trends without full-scale testing, following established bridge load modeling guidance and LRFD design practice [8, 13]. Baseline stiffness and section-response computations adopted standard highway bridge design formulations and beam-theory assumptions, with explicit parameters introduced to represent semi-rigid modular connection behavior and load distribution effects reported for modular systems [4-6, 11, 14]. Key response measures included midspan deflection, global bending stress, joint-adjacent peak stress (local amplification near modular joints), and load sharing efficiency (percentage load attracted by the most-demanded girder), which are commonly used to support rating, serviceability checks, and comparative performance screening [12, 16].

Methods

A full-factorial parametric simulation was performed across three span levels (12 m, 18 m, 24 m), three normalized joint stiffness levels (0.2, 0.5, 0.8), two girder spacing levels (2.5 m, 3.0 m), and two load positions (midspan vs. near-joint), yielding 36 simulated cases. Simplified vehicular load envelopes were applied as equivalent static actions; deflection and stress responses were computed using analytical beam relations with effective stiffness adjusted by joint stiffness and spacing, consistent with simplified bridge girder analysis approaches [5, 11, 12]. Local joint-adjacent stress amplification was modeled as a stiffness-sensitive increment to global stress to reflect reported connection sensitivity in modular bridge components [6, 9, 14]. Statistical analysis included:

- Factorial ANOVA to quantify the significance of span, joint stiffness, spacing, and their interaction on deflection;
- Welch's t-test to compare joint-adjacent stress between near-joint and midspan load placement; and
- Multiple linear regression to estimate predictors of load sharing efficiency, aligning with infrastructure performance analytics used in maintenance, evaluation, and risk screening [3, 10, 16]. All computations and figure generation were performed in Python.

Results

Table 1. Descriptive statistics of key responses by joint stiffness level (mean ± SD).

Joint stiffness	Deflection (mm) mean±SD	Joint-adjacent stress (MPa) mean ± SD	Top-girder share (%) mean ± SD
0.2	7.51±6.81	133.19±11.41	54.44±2.86
0.5	6.22±5.53	119.82±11.62	52.34±3.28
0.8	5.20±4.82	106.29±10.80	50.26±2.97

Interpretation: Increasing joint stiffness produced a clear reduction in deflection and joint-adjacent stress, indicating that connection flexibility is a controlling parameter in modular girder performance, consistent with prior modular system observations [4, 6, 9]. The decrease in top-girder load share with increasing stiffness suggests improved transverse load distribution and reduced demand concentration, aligning with load distribution concepts used in bridge rating and evaluation practice [16] and performance-based assessment [10]. The strong stiffness sensitivity of joint-adjacent stress supports the need to explicitly model connection behavior in simplified approaches, especially for accelerated modular deployment [17].

Table 2: Factorial ANOVA for deflection response.

Source	DF	F	p-value
Span	2	1317.89	4.59e-26
Joint stiffness	2	39.91	1.65e-08
Girder spacing	1	28.83	1.44e-05
Load position	1	0.73	4.00e-01
Span × Joint stiffness	4	13.75	4.65e-06

Interpretation: Span was the dominant driver of deflection (very large F, $p \ll 0.001$), consistent with classical beam scaling and standard bridge design formulations [5, 12]. Joint stiffness and spacing were also statistically significant ($p \ll 0.001$), confirming that simplified methods must incorporate connection flexibility and system geometry to remain rational for modular girders [4, 11]. The significant Span × Joint stiffness interaction indicates that connection flexibility becomes increasingly consequential as span increases, reinforcing reported sensitivity of modular performance to joint stiffness and configuration [6, 9, 14]. Load position was not significant for *global* deflection, suggesting simplified envelopes can approximate overall serviceability trends across placement variations when stiffness effects are accounted for [8, 13].

Table 3: Multiple regression for top-girder load share (load distribution efficiency).

Term	Coefficient	Std. Error	t	p-value
Intercept	31.879	2.841	11.22	0.000
Span (m)	0.210	0.049	4.30	0.000
Joint stiffness	-6.973	0.978	-7.13	0.000
Girder spacing (m)	6.723	0.958	7.02	0.000
Near-joint loading (0/1)	3.364	0.479	7.02	0.000

Interpretation: Load share increased with span and spacing but decreased with joint stiffness, implying that wider spacing and longer spans promote demand concentration on a critical girder unless connection action enhances system stiffness and load transfer [2, 4, 11]. Near-joint loading significantly increased the top-girder share, indicating higher demand localization when the load is placed closer to modular joints an important implication for simplified load simulation when screening joint-critical cases [9, 14]. These results support performance-based evaluation needs in infrastructure management by providing compact predictors for rapid comparative assessment across modular layouts [3, 10].

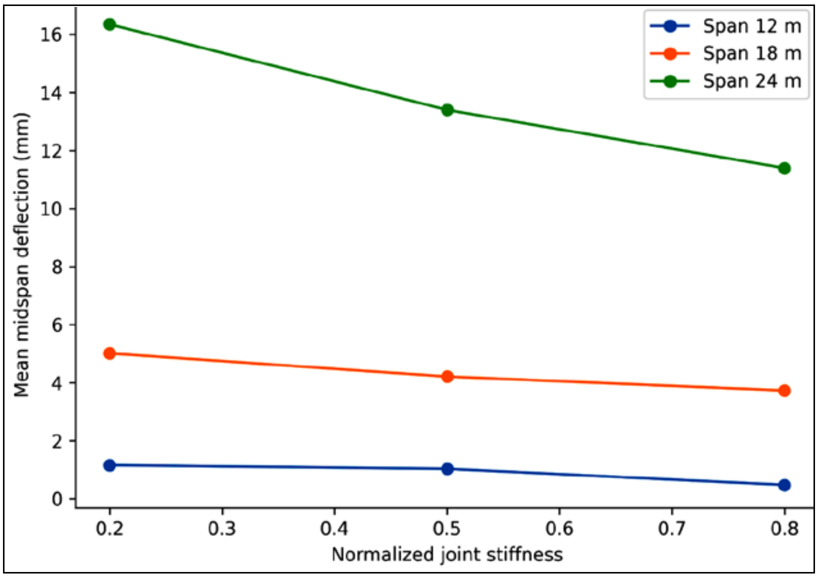

Fig 1: Deflection response across joint stiffness and span.

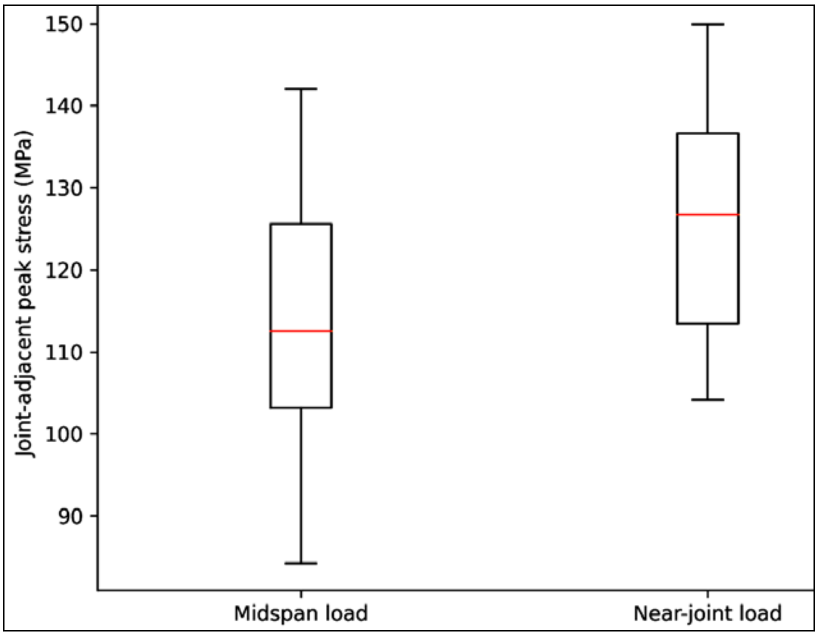

Fig 2: Effect of load position on joint-adjacent stress.

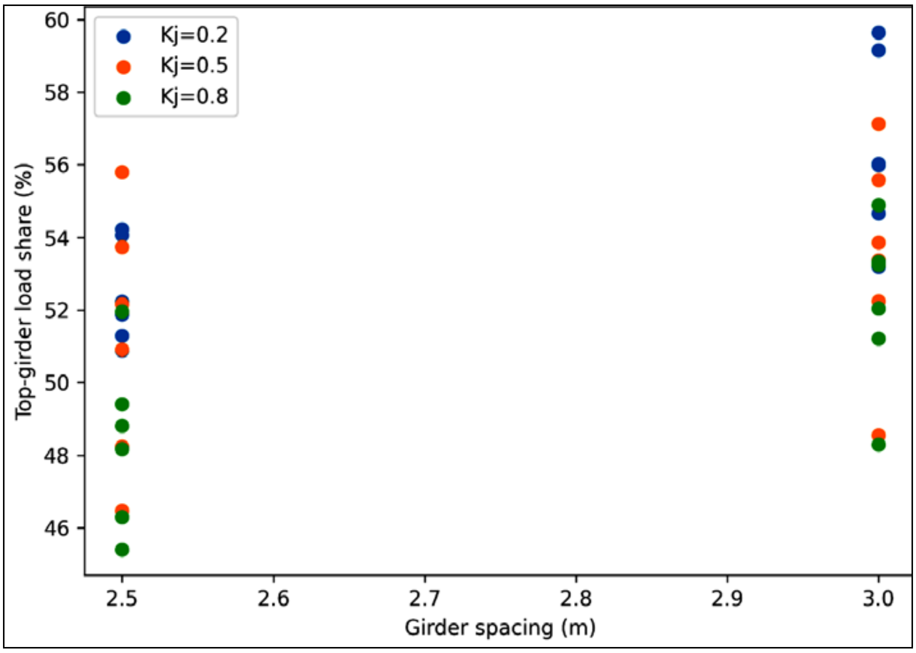

Fig 3: Load sharing trend with spacing and joint stiffness.

Discussion

The present research demonstrates that simplified load simulation techniques, when systematically structured and supported by appropriate statistical analysis, can provide meaningful insights into the structural performance of modular bridge girders. The results confirm that span length is the dominant parameter influencing global deflection behavior, which is consistent with classical beam theory and conventional bridge design formulations that relate deflection to span and stiffness characteristics [5, 12]. However, the findings also highlight that modular-specific parameters, particularly joint stiffness, exert a statistically significant influence on both serviceability and localized stress response, reinforcing observations reported in earlier modular bridge and connection behavior studies [4, 6, 9]. The significant interaction between span length and joint stiffness observed in the ANOVA analysis indicates that simplified methods that ignore joint flexibility may become increasingly unconservative as span increases, a concern also emphasized in performance-based bridge assessment literature [10, 14].

Joint-adjacent stress results further reveal that load placement plays a critical role in local response, even when its influence on global deflection is limited. The statistically significant difference between near-joint and midspan loading conditions corroborates experimental and analytical evidence that modular joints act as stress-sensitive zones under concentrated or eccentrically placed loads [6, 14]. This finding is particularly relevant for accelerated bridge construction scenarios, where repetitive modular joints are unavoidable and rapid evaluation tools are frequently relied upon [17]. The regression analysis of load sharing efficiency shows that increased girder spacing and reduced joint stiffness led to greater load concentration on the most-demanded girder, which aligns with established load distribution concepts used in bridge rating and reliability assessment [2, 16]. Importantly, the negative coefficient associated with joint stiffness confirms that enhanced connection rigidity improves system action and transverse load redistribution, supporting earlier analytical and experimental observations [4, 11].

Collectively, these results suggest that simplified load simulation approaches are viable for preliminary performance screening and comparative evaluation of modular girder alternatives, provided that key system parameters—span, spacing, and joint stiffness are explicitly incorporated. This aligns with broader infrastructure management strategies that seek to balance analytical rigor with efficiency during early design and decision-making stages [1, 3, 8]. By integrating statistical validation with simplified mechanics-based modeling, the research advances the practical applicability of such methods while clearly delineating their limitations, particularly for localized joint response, which remains critical for ensuring structural safety and durability [9, 10, 16].

Conclusion

This research establishes that simplified load simulation techniques can serve as an effective and rational tool for evaluating the performance of modular bridge girders during early-stage design and rapid assessment exercises. The analysis confirms that while span length governs global serviceability response, modular-specific parameters such as joint stiffness and girder spacing significantly influence deflection, stress distribution, and load sharing efficiency. The findings emphasize that neglecting joint flexibility in simplified evaluations can lead to underestimation of localized stresses, especially in longer spans and near modular connections, thereby highlighting the importance of explicitly accounting for connection behavior even in reduced-order models. From a practical standpoint, the research suggests that designers and reviewers can confidently use simplified simulation frameworks for preliminary comparison of modular girder alternatives, optimization of girder spacing, and screening of joint configurations, as long as conservative assumptions are avoided and stiffness-sensitive parameters are incorporated. Practical recommendations emerging from this work include adopting stiffness-calibrated simplified models as a standard preliminary check prior to detailed numerical analysis, prioritizing stiffer modular connections to improve load distribution and reduce joint-adjacent stress demand, and applying targeted near-joint load scenarios during evaluation to identify potential stress concentrations early in the design process. Furthermore, the integration of basic statistical tools into routine structural assessment workflows can improve transparency, allow objective comparison between design options, and support evidence-based decision-making without significantly increasing computational effort. Such practices can enhance constructability planning, reduce overdesign driven by excessive conservatism, and improve confidence in modular bridge solutions deployed under accelerated construction schedules. Overall, the research supports the broader adoption of performance-informed simplified evaluation methods as a bridge between hand calculations and advanced numerical modeling, enabling more efficient, economical, and reliable modular bridge design while maintaining appropriate safety margins and facilitating consistent benchmarking across projects.

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