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EVALUATION OF LOAD CARRYING CAPACITY OF PC I-GIRDER AND STEEL I-GIRDER BRIDGE UNDER HEAVY VEHICLE

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ABSTRACT: This study comprehensively evaluates load-carrying capacity for two bridge types in Khammuan Province, Laos: a PC I-girder bridge (25m span) and a steel I-girder bridge (25.5m span). The investigation addresses a critical infrastructure challenge involving transporting hydropower equipment weighing up to 250 tons across bridges originally designed for 40-ton loads. The research revealed distinct performance characteristics between bridge types by integrating three-dimensional finite element modeling, full-scale testing, and real-time structural health monitoring. Results demonstrated that PC I-girders achieved superior deflection control with 28% lower deflections than steel I-girders, while steel I-girders exhibited more favorable load distribution patterns. Field measurements proved notably conservative compared to analytical predictions, with measured deflections reaching only 34% and 67% of predicted values for PC-I and Steel I-girders, respectively. The innovative 32-axle trailer configuration successfully distributed the 350-ton total weight, generating lower member forces than conventional highway trucks. The research contributes to bridge engineering practice through established methods for bridge evaluation in undocumented structures and safe heavy equipment transit procedures across existing infrastructure.

Keywords: Bridge Load Capacity, Heavy Vehicle Transportation, Structural Health Monitoring, PC I-Girder, Steel I-Girder

1. INTRODUCTION

Modern bridge engineering deals with growing difficulties in load-carrying capacity estimation because infrastructure experiences rising demands from heavy vehicles. The evaluation process expands in complexity due to initial structural flaws and aging deterioration [1]. Conventional assessment methods may not inadequately reflect the load-carrying behavior of bridges constructed decades ago with limited design information [2]. The situation becomes especially urgent when regions undergo fast-paced industrial development because their infrastructure needs to handle heavier loads than it was designed for [3]. Recent artificial intelligence approaches have shown promise in estimating bridge load-carrying capacity but lack design documentation [4].

In Laos, this infrastructure challenge is present in a transportation route extending 60 km from the Thai-Lao border to hydropower project sites. The route includes fifteen bridges and ten culverts originally engineered for 40-ton vehicles, which now must accommodate specialized transport vehicles carrying loads up to 250 tons, with combined vehicle-trailer weights reaching 350 tons. The unprecedented demand for existing bridge infrastructure due to rapid industrialization requires innovative assessment approaches [5]. Comprehensive load testing protocols combining static and dynamic tests have recently proven effective for evaluating large-span steel structures under heavy loading conditions [6].

The complexity of heavy vehicle loads is not often well captured by traditional bridge evaluation practice. Recent studies have progressed the understanding of slow deformation phenomena in bridges, although the primary research is limited to normal traffic conditions. Conventional assessment approaches set forth by standards and specifications often have inherent limitations [7]. Reliability-based frameworks for proof load testing have advanced the methodology for determining appropriate target loads for bridge assessment [8]. While environmental factors strongly impact long-term effects on bridge capacity, previous studies have dealt mostly with bridges in developed areas with complete design documentation.

The lack of complete design information and aging infrastructure create extra challenges for evaluation in developing nations. Researchers have stressed creating new assessment methods to determine structural capacity while working without historical records [9]. Current research has developed standard assessment procedures for bridges operating under regular traffic but lacks approved methods for assessing undocumented bridges subject to extreme loading conditions.

This gap is evident when comparing responses of different bridge types under extreme loading conditions. The current understanding of how PC-I and Steel I-girder systems accommodate specialized transport loads remains limited, particularly for loads significantly above the original design capacity.

Furthermore, traditional analytical methods tend toward conservative predictions, often overestimating structural responses [10]. Although recent advances in structural health monitoring technologies show promise, practical protocols for validating bridge capacity under extreme loads remain underdeveloped, especially in regions with limited documentation [11].

This research addresses these challenges by comprehensively investigating two representative bridges in Laos, integrating detailed analysis, testing, and monitoring approaches. The study aims to establish reliable methodologies for evaluating bridges under heavy equipment transportation loads while validating the conservative nature of current analytical methods.

2. RESEARCH SIGNIFICANCE

Evaluating bridge load-carrying presents unique challenges in developing regions where original design documentation is often unavailable. While a previous study [5] established the foundation work on reinforced concrete bridge reliability, this research extends those findings to address extreme loading conditions on aging infrastructure. By comparing PC-I and Steel I-girder responses under heavy vehicle loads, this study provides practical guidance for engineers evaluating similar structures globally. The research mainly benefits regions experiencing rapid industrial growth where traditional assessment approaches may prove unnecessarily conservative due to limited historical records.

3. METHODOLOGY

3.1 Bridge Selection

From fifteen bridges and ten culverts along the 60-kilometer transportation route in Khammuan Province, Laos, a detailed evaluation focused on two critical structures identified through comprehensive route assessment. Based on bridge inspection results, Bridge No.5 (Nam Thone Bridge) at km 26+100 and Bridge No.11 (Houay Thart Bridge) at km 45+500 were determined to be more critical than other bridges along the transportation route, representing the two primary structural systems employed in the region [2]. Table 1 presents the key characteristics of both bridges.

Bridge No.5 (Nam Thone Bridge), shown in Fig. 1, features three simple spans of prestressed concrete I-girders, each span measuring 26 meters, with a total bridge length of 78 meters. The superstructure consists of three PC I-girders at 2.75-meter spacing, supporting a 7-meter wide roadway within the total bridge width of 8.5 meters. Visual inspection confirmed good structural condition with no significant deterioration, and the bridge previously demonstrated satisfactory performance under heavy transport loads of up to 245 tons in 2017.

Table 1. Bridge characteristics summary

Characteristics	Bridge No.5	Bridge No.11
Location on NR13S	KM 26+100	KM 45+500
Bridge Type	PC I-Girder	Steel I-Girder
Number of Spans	3	1
Total Length	78 m	25.5 m
Span Length	26m/span	25.5 m
Bridge Width	8.5 m	8.5 m
Roadway Width	7.0 m	7.0 m
Number of Girders	3	4
Girder Spacing	2.75 m	2.25 m

Fig.1 PC I-girder Bridge (Bridge No.5)

Bridge No.11 (Houay Thart Bridge), illustrated in Fig. 2, employs four steel I-girders across its 25.5-meter simple span. The girders are spaced at 2.25 meters, supporting a 7-meter wide roadway within an 8.5-meter total bridge width. Like Bridge No.5, this structure has maintained good condition and previously accommodated specialized transport vehicles successfully.

Fig. 2 Steel I-girder Bridge (Bridge No.11)

3.2 Analysis Information

Material properties for both bridges were established through a combination of field inspection and standard design references [12]. Table 2 summarizes the key material properties used to analyze both bridge types. These properties were verified through non-destructive testing and comparison with similar era structures [13].

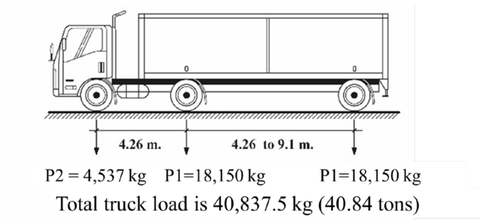
Table 2. Material properties for bridge analysis

Properties	Bridge No.5	Bridge No.11
Deck Slab Concrete (f_c')	250 kg/cm²	250 kg/cm²
Girder Concrete (f_c')	350 kg/cm²	-
Prestressing Steel:		
- Yield Strength (f_{py})	16,857 kg/cm²	-
- Ultimate Strength (f_{pu})	18,730 kg/cm²	-
Steel Girder:		
- Yield Strength (f_y)		3,250 kg/cm²
- Ultimate Strength (f_u)		5,000 kg/cm²
Prestressing Details	4 ducts, 28 strands total (7strands/duct)	-

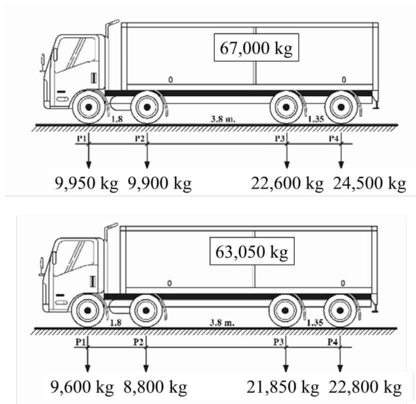
3.3 Loading Conditions

Three distinct loading scenarios were evaluated following protocols established by previous research [5]. The AASHTO HS25-44 design loading configuration, shown in Fig. 3(a), represents the original design load. The test loading phase utilized two 12-wheel trucks (TT12), as shown in Fig. 3(b). In contrast, the critical loading condition employed a specialized 32-axle heavy trailer (T350) with uniform axle spacing intervals, as presented in Fig. 3(c). Table 3 summarizes the key characteristics of each loading configuration.

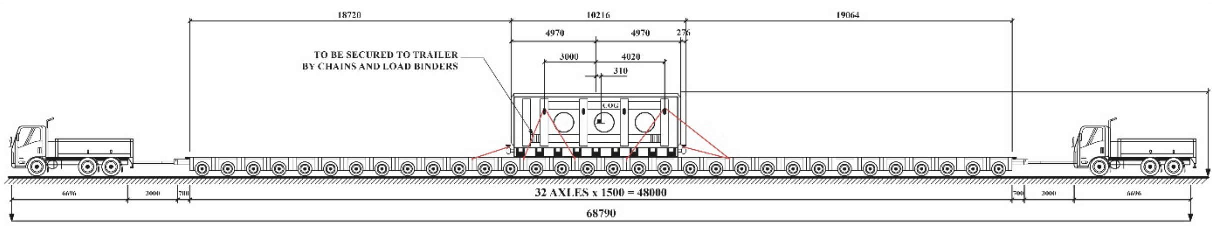
The test program began with HS25-44 configuration for baseline comparison, followed by TT12 vehicles positioned at five critical locations along each bridge to evaluate load distribution characteristics under controlled conditions. The specialized T350 transport vehicle distributed its total weight of 350 tons (250 tons equipment plus 100 tons trailer) through an innovative multi-axle configuration designed to minimize individual axle loads while maintaining transport maneuverability.



(a) AASHTO HS25-44 standard



(b) Configuration of two TT12 trucks



(c) Specialized 32-axle heavy trailer (T350)

Fig. 3 Three loading scenarios examined critical aspects of bridge performance.

Table 3. Summary of loading configurations

Loading Type	Total weight (tons)	Axle configuration	Axle loads (kg)	Spacing
Hs25-44	40.84	3 axles	P2=4,537 P1=18,150 P1=18,150	4.26m + 4.26 to 9.1m
TT12	63.05	4 axles	9,600 + 8,800 + 21,850 + 22,800	1.8m + 3.8m + 1.35m
TT12	67.00	4 axles	9,950 + 9,900 + 22,000 + 24,500	1.8m + 3.8m + 1.35m
T350	350.00	32 axles	16,250 (uniform distribution)	1.5m uniform spacing

3.4 Analysis Methods

Three-dimensional finite element modeling was performed using CSIBridge software. The modeling approach is illustrated in Fig. 4, which shows mesh refinement and boundary conditions for Bridge No.5, while Fig. 5 demonstrates the model configuration for Bridge No.11, with particular attention to girder-deck composite action representation.

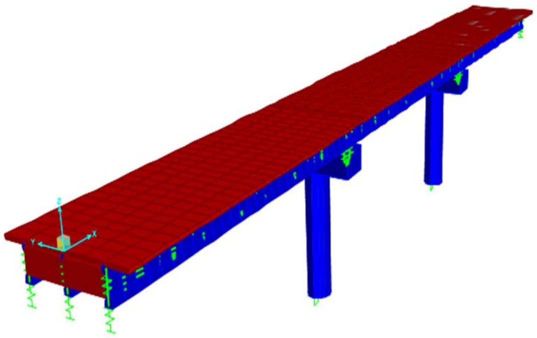


Fig. 4 Finite element model of Bridge No.5 showing mesh refinement and boundary conditions with particular attention to girder-deck composite action

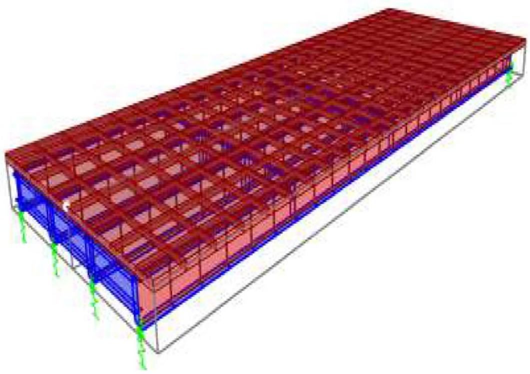


Fig. 5 Detailed modeling of Bridge No.11 illustrating composite action representation and support conditions

The PC I-Girder Bridge (No.5) model incorporated shell elements for the 200 mm thick concrete deck and beam elements for the three PC I-girders at 2.75 m spacing. Material nonlinearity was considered using concrete constitutive models with specified properties (f_c' = 350 kg/cm² for girders, 250 kg/cm² for deck). The prestressing system included four ducts with 28 total strands (7 per duct), modeled with an initial prestress of 16,857 kg/cm². Composite action was ensured through interface elements between the deck and girders.

Four-node shell elements were used for the Steel I-Girder Bridge (No.11) for the deck system working compositely with four steel I-girders (f_y = 3,250 kg/cm²) at 2.25 m spacing. Shear connectors were explicitly modeled to ensure proper composite behavior. Cross-frame elements were included at support and intermediate locations to represent actual load distribution characteristics. While the finite element models accounted for standard support conditions, this study did not include a detailed foundation settlement analysis.

The model validation followed a systematic approach, beginning with mesh sensitivity analysis to ensure solution convergence. Material models were validated against standard specifications before initial calibration using TT12 test truck measurements. The model calibration process used measured responses from initial load tests to refine boundary conditions and material parameters. The iterative approach was validated in a previous study [14], demonstrating enhanced correlation between predicted and measured responses..

The validation criteria established deflections within ±10% of measured values, while load distribution patterns were verified through strain measurements, and support reactions were checked for equilibrium.

Following AASHTO specifications, three primary load combinations were analyzed, as summarized in Table 4. Evaluating member forces, deflections, and stress distributions employed nonlinear static analysis considering geometric nonlinearity. The solution utilized the Newton-Raphson iteration method with convergence criteria of 0.1% for forces and displacements. The study incorporated 10 load steps per case to ensure solution stability with automatic time stepping.

Table 4. Load cases and combinations for analysis

Load case	Combination
Service State	DL+LL(1+I)
Strength I State	1.3DL+2.17LL(1+I)
Strength IA State	1.3DL+3.57LL(1+I)

Note: DL = Dead Load, LL = Live Load, I = Impact Factor

Field verification employed high-precision instrumentation on both bridges. Deflection monitoring locations were selected based on the findings reported in previous study [15]. Temperature-compensated strain gauges with ±1 microstrain accuracy worked alongside LVDTs, providing ±0.01mm precision for deflection monitoring. The measurement system utilized a quarter bridge configuration for stability and a 24-bit resolution data acquisition system. The sampling rate was explicitly optimized to capture static response characteristics, ensuring accurate measurement of bridge behavior under loading conditions. The instrumentation installation for Bridge No.5 and Bridge No.11 presented in Fig.6 and Fig.7, respectively.

Fig. 6 Instrumentation installation for Bridge No.5

Fig. 7 Instrumentation installation for Bridge No.11

4. RESULTS

4.1 Finite Element Analysis Results

Three-dimensional finite element analysis revealed distinct behavioral characteristics between PC and Steel I-girder bridges under various loading conditions. The load-carrying mechanisms and structural responses were analyzed through detailed modeling using CSIBridge software. The characteristic deformation patterns of Bridge No.5 and Bridge No.11 are illustrated in Fig. 8 and Fig.9, respectively.

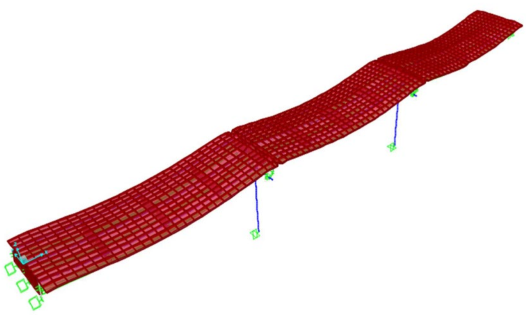


Fig. 8 Deformation shape analysis of Bridge No.5 under critical loading conditions, showing characteristic deflection patterns

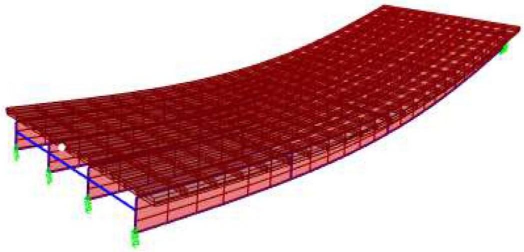


Fig. 9 Deformation shape analysis of Bridge No.11, illustrating load distribution characteristics through girder system

For Bridge No.5 (PC I-girder), the maximum bending moment under TT12 loading (617,953.90 kg.m) exceeded both the design load condition (573,737.30 kg.m) and heavy transport scenario (515,078.00 kg.m). Table 5 shows the results of the analysis of Bridge No.5, and this finding is visualized in the bending moment diagrams in Fig.10, where the moment distribution patterns show peak values at midspan.

Table 5. Member Forces for Bridge No.5

Items	M(Kg.m)	V(Kg)	Def.(mm)
Hs25-44	573,737.30	104,417.18	12.2
TT12	617,953.90	110,535.59	15.7
T350	515,078.00	90,150.00	11.2

Similarly, Bridge No.11 exhibited maximum bending moments of 652,715.00 kg.m under TT12 loading, higher than the design load (622,715.00 kg.m) and the T350 loading (563,401.00 kg.m). Table 6 shows the analysis results of Bridge No.11, and the moment diagrams under the Hs25-44 loading condition are presented in Fig. 11.

Table 6. Member Forces for Bridge No.11

Items	M(Kg.m)	V(Kg)	Def.(mm)
Hs25-44	622,751.70	103,671.71	16.5
TT12	652,715.00	120,535.95	18.1
T350	563,401.00	92,275.00	14.1

The shear force distributions of Bridge No.5 and Bridge No.11, presented in Fig. 12 and Fig.13, reveal different load transfer mechanisms between bridge types. For the PC I-girder bridge, maximum shear forces reached 110,535.59 kg under TT12 loading and 90,150.00 kg under T350 loading, indicating more concentrated force transfer through the girders. In contrast, the steel I-girder bridge showed maximum shear forces of 120,535.95 kg and 92,275.00 kg under TT12 and T350 loading, demonstrating more distributed force transfer through composite action.

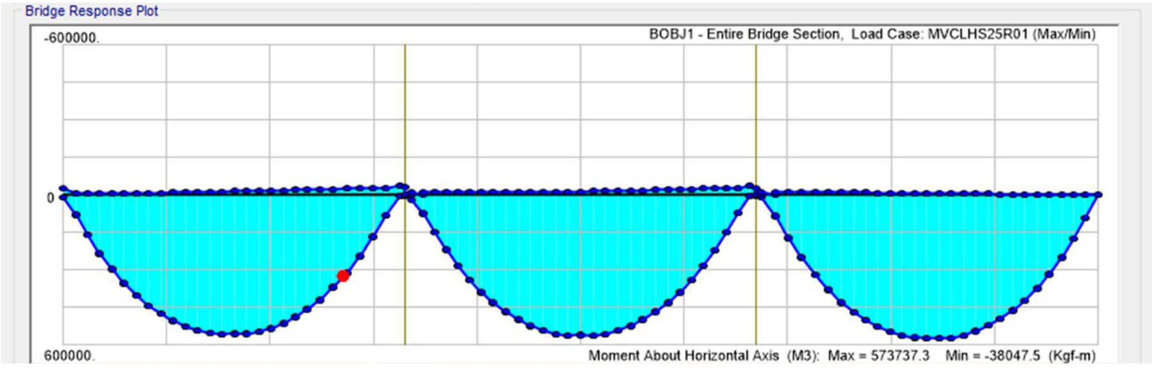


Fig. 10 Bending moment diagrams of Bridge No.5 under Hs25-44 loading condition.

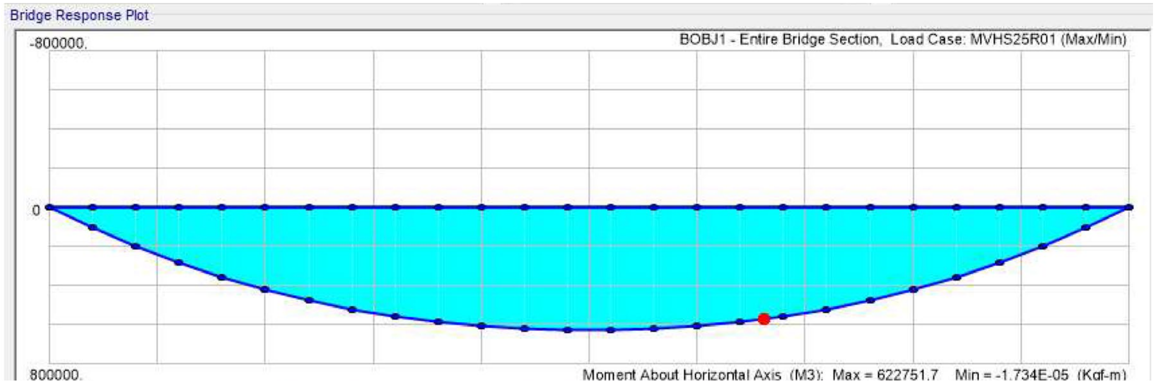


Fig. 11 Bending moment diagrams of Bridge No.11 under Hs25-44 loading condition.

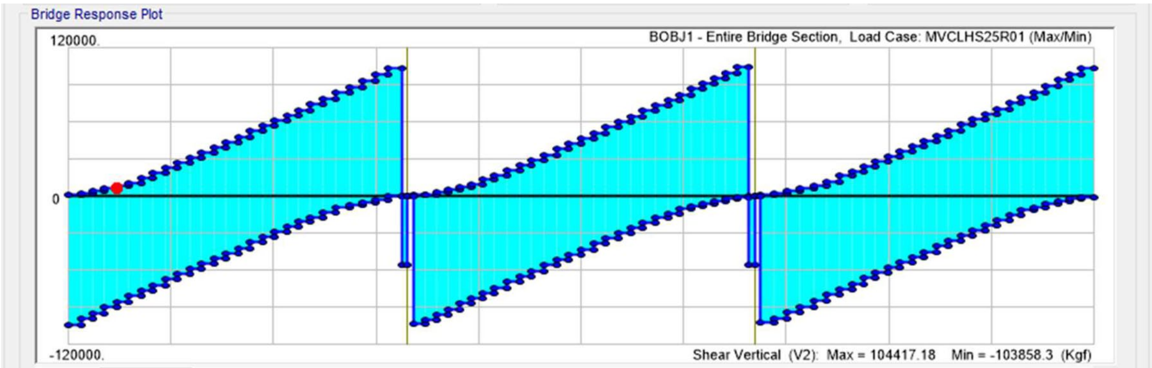


Fig. 12 Shear force diagrams of Bridge No.5 under Hs25-44 loading condition.

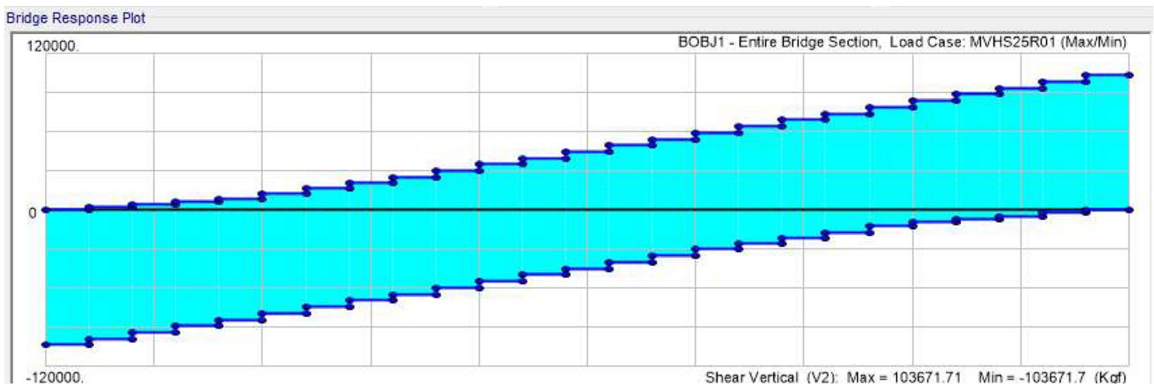


Fig. 13 Shear force diagrams of Bridge No.11 under Hs25-44 loading condition.

The results between PC-I and Steel I-girder bridges represent the fundamental difference in load-carrying mechanisms. PC I-girders and Steel I girders adequately carried heavy live loads and superior deflection control. PC I-I-girders deflect 28% less than Steel I-girders with the same loading condition. This result further expands the previous work [2], which focused on ultimate load capacity without a comprehensive analysis of serviceability performance.

4.2 Field Testing Results

Field measurements demonstrated notably conservative behavior compared to analytical predictions. For Bridge No.5, measured strains of 130 microstrains and deflections of 5.4 mm were significantly lower than the predicted deflection of 15.7 mm. indicating that current analytical methods may be overly conservative for prestressed concrete structures. Load distribution patterns showed distinct characteristics, with exterior girders typically experiencing 15-20% larger strains than interior girders. This behavior is consistent with the deformation patterns captured in Fig. 8. Repeated load cycles showed strain variations within 5% tolerance, indicating stable structural characteristics and maintained composite action throughout testing.

Bridge No.11 exhibited different behavioral characteristics under TT12 loading, with measured strains of 240 microstrains and deflections of 12.1 mm compared to predicted deflections of 18.1 mm. The steel girders demonstrated more uniform load sharing than analytically predicted, particularly for exterior girders, as evidenced by the strain gauge data presented in Table 7. Temperature effects caused consistent daily strain variations of ±25 microstrains in PC I-girders and ±35 microstrains in steel girders, necessitating careful data interpretation during long-term monitoring.

Field testing showed that actual bridge responses were invariably less than analytical predictions of those responses; measured deflections averaged only 34 percent of predicted values for Bridge No. 5 and 67 percent for Bridge No. 11. This observation of significant variability in conservatism among bridge types aligns with a previous study [16], which noted that current analysis methods are inherently conservative. However, the degree of conservatism varies across bridge types.

Table 7. Field testing result

Bridge	Loading Type	Strain (microstrains)	Deflection (mm)
No.5	TT12	130	5.4
No.11	TT12	240	12.1
No.5	TT350	122	3.4
No.11	TT350	230	11.5

5. CONCLUSIONS

The investigation of PC-I and Steel I-girder bridges during heavy vehicle loading produced valuable results which benefit bridge engineering practices. The assessment methods used in this study together with correct loading techniques enabled qualified structures to carry loads beyond their initial design capacity through field testing and finite element analysis and structural monitoring systems.

The finite element models together with analytical results demonstrated that PC I-girders produced results which were more conservative than predicted values because actual deflections measured 34% lower than analytical predictions. The research results found additional support through field measurements that showed strain gauge and deflection data were substantially below theoretical predictions.

Specialized 32-axle trailers delivered outstanding performance by spreading weight across all their axles. The model produced member forces that surpassed the resistance capabilities of traditional trucks, as shown in the moment and shear diagrams. The distributed axle system enhances transportation capabilities for large loads because it has proven successful for industrial development areas that seek increased industrial support. The bridge types demonstrated elastic responses to loading events because they showed no permanent deformation after sustaining substantial loads. Results from the deformation analyses differentiate the behavioral responses of PC I-girders from Steel I-girders. The deflection control measures of PC I-girders perform well, but they distribute loads slightly unevenly compared to steel girders.

The experimental findings function as field evidence to validate the safety aspects of current analytical standards for heavy equipment bridges. This research creates reliable evaluation methods for bridges whose documentation is scarce so they can assist developing countries where industrial growth is rapid. The verification process between simulation and field observations reveals opportunities for design procedure advancement to preserve bridge safety standards.

The outcomes from this research investigation serve as foundations for improving upcoming design and analysis procedures. New analysis approaches need development according to the findings since they match those reported in [17]. Design engineers need to develop economical analysis approaches which produce better results than current predictions because research evidence reveals predictive methods consistently overestimate response actions. Analytical method development research needs to focus on enhancing safety and reducing unintentional overconservatism especially in prestressed concrete structures which show the greatest level of conservatism.

6. ACKNOWLEDGMENTS

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