

Structural health monitoring of existing highway bridges to improve infrastructure sustainability: Experimental testing and numerical simulation

Ali Sheheed Radhi^{1*}, Ali Fadhil Naser²

^{1,2} Al-Furat Al-Awsat Technical University- Al-Mussaib Technical College -Building & Construction Department, Babylon, Iraq.

*Correspondence: Ali Sheheed Radhi, Tel : +9647810093643 Email : ali.shaheed.tcm38@student.atu.edu.iq

Received 30/05/2026 Received in revised form 29/06/2026
Accepted 08/07/2026, Available online 10/10/2026

FJIAS 2026, 2(S1): 111-140

Special Issue: Selected Papers from the 3rd International Conference on Sustainable Development and Climate Change (ICSDCC 2026). Organized by Al-Mussaib Technical College / Al-Furat Al-Awsat Technical University, Iraq, in cooperation with Delta University for Science and Technology, Egypt. Held at Delta University for Science and Technology, Mansoura, Egypt, on 18 July 2026.

ABSTRACT

Sustainable development of the transportation infrastructure is one of the most significant worldwide challenges in the future, particularly to ensure the safety and functionality of existing highway bridges as they have been for centuries, as the higher traffic volume continues to combine with environmental changes. Using overpass bridges investigation on Hilla–Kish Expressway, a vital regional highway in Iraq, as a case study, this research investigates the health of such bridges. In this study, it selected a combined field static loading test and structural monitoring analysis numerical simulation method. Field data were gathered wherein the deflections and strains at selected critical locations on the bridge girders were determined under well-controlled loading conditions. Simultaneously, a full-fidelity 3D finite element model was developed in CSIBridge, driven by the same loading to replicate structural response. It shows that the agreement between both the experimental and the numerical results is excellent, which demonstrates the reliability of this FEM model for future forecasting. This study enables the extension of the service life of bridges by reducing the environmental and economic costs associated with the premature replacement of such infrastructure through the accurate determination of the live-load distribution and stiffness of the bridge components, i.e., the superstructure and substructure. These results will feed into the Engineering Research" axis of the conference by showing that accurate structural assessment can serve as a fundamental building block of sustainable, globally distributed infrastructure management and climate-adapted engineering.

Keywords: Static Load Testing, Finite Element, AASHTO LRFD Standards, Stress Analysis, Deflection Analysis

1. Introduction

Highway bridges are vital parts of the transportation infrastructure network that promote social and economic development. But, these structures are usually damaged by environmental actions and loadings, resulting in large danger and a short service life. Evaluating the general state of these bridges is important for the purposes of maintenance and safety management (Singh & Maru, 2023; Tu et al., 2023; A. L. I. F. Naser & Zonglin, 2011; Structures, 2015; Brinissat et al., 2024; Terranova et al., 2012).

Prompt detection of different kinds of damage (concrete carbonation, reinforcement corrosion, and cracks). The foremost means by which we identify these defects and the need for either repair or strengthening, to ensure a bridge remains in service and is safe, is field damage inspection (A. F. Naser & Wang, 2011; Ahmed et al., 2020; Hasani Hamed & Francesco Freddi, 2023; Mlv, 2020; Chavel, 2012; Zhang et al., 2022; Ritter, 1990; Boldrin et al., 2024).

Highway networks have modern construction methods that often use complex bridge geometries like skewed bridges or horizontally curved box girder bridges. Such structures show characteristic structural responses, including complex stress distributions and coupled bending-torsion effects that must be accurately assessed under static and dynamic loads (Landge et al., 2018; Kolhe & Shiyekar, 2023).

Static load test is a fast, high-precision and economical method to measure the effective bearing capacity and stiffness of the bridge. Finite Element Method (FEM) analysis software is used to validate these field results. Structural assessment by parameter testing is generally represented by comparing measured site data with theoretical numerical results and commonly expressed via 'verification coefficient' (Sun et al., 2019; Spencer et al., 2019; Cai et al., 2012; Xu et al., 2025; Freddi, 2023; You et al., 2025a).

The internal forces(e.g. the bending moment & shear force of pier, etc.) and stability of bridge is heavily dependent on the geometric properties of the bridge, e.g. pier height, super-elevation rate, & etc. Mathematical modeling is a necessary tool to enable understanding of these effects for appropriate structural assessments (A. F. Naser et al., 2021; NASER, 2021; M. Kumar et al., 2018; Iacovino et al., 2022; Komarizadehasl et al., 2022; Panigati et al., 2025).

Static load testing is a simple, high precision, and cost-effective procedure to measure the actual bearing capacity and stiffness of the entire bridge FEM Analysis is performed using software to validate these field results. This includes the comparison of measured field data and theoretical numerical results, usually expressed in terms of the so-called verification coefficient is a standard for structural evaluation (A. F. Naser & Wang, 2011; Mohammed & Naser, 2020; Boldrin et al., 2024; Kee et al., 2012; Nowotarski et al., 2017).

Internal forces (bending moments; shear forces) and the stability of bridges are significantly affected by geometric factors including pier height and super-elevation rates. Mathematical modelling is necessary to realise these effects for structural assessment (Cai et al., 2012; Ni et al., 2023; Aliyari et al., 2021; Bougard et al., 2008; Liu, 2026; Gatesi et al., 2020).

Durability of highway bridges is significantly affected by environmental factors and the increasingly high loading due to traffic. Concrete deterioration and the corrosion of structural steel reinforcement occur and their accumulation over time causes the ensuing gradual rate of gradual loss of structural stiffness. Such assessment of varying modes of transport and loading combinations in contentions with bending moments and vertical displacement is important for estimating the residual lifespan of the infrastructure(Lantsoght, 2023; Wang et al., 2024; Vardanega et al., 2024; M. H. Kumar, 2018; Döring et al., 2011).

Features of professional bridge aspects, like the bridge deck, expansion joints, and piers, significantly influence the general fitness of its system. Problems like water dropping through joints or freezing of concrete surfaces lead to the fast rate of decay of the substructure. Advanced sensing technologies and optical survey equipment (utilized during load tests) allows for accurate quantification of load transfer and distribution between these components (Ryan et al., 2022; Chavel, 2012; Alampalli & Jalinoos, 2009; Garnica et al., 2021).

In this context, the traditional approaches to bridge evaluation are generally based on information provided as a single deterministic value (usually the verification coefficient from a load test). Nevertheless, the application of reliability theory is emerging to assess the behaviours of bridge. Tools help engineers to compare the actual structural reliability to the design requirements, and they provide a stronger foundation for making decisions related to bridge maintenance and rehabilitation (You et al., 2025b; A. F. Naser, 2018; Abad et al., 2021).

Static load test is one of sustainable detection way needed for the highway bridge real stiffness & bearing capacity, which is used to assess the operating state and safety of the bridge. They include setting heavy vehicles (e.g., HB-AH1 or regular trucks) in order to simulate design load effects and measure important properties (i.e., vertical deflection and strain) using high-accuracy sensors and optical survey equipment. These results directly evaluate the elasticity of the bridge, for example, the verification coefficient, which is the measured value divided by the theoretical value, should be less than a certain limit in order to be in service safely. In addition, this testing is essential for defect identification of individual elements such as bridge decks and box girder segments. (Khudair et al., 2025).

Recently, the Finite Element Method (FEM) numerical modelling has established itself as a powerful tool for bridge assessment by enabling unprecedented details in both static and dynamic simulations while offering versatility in loading conditions simulation. This is processed using high-level software where bridges are divided into solid elements, enabling a good process of stress distribution. This approach becomes indispensable in realizing some of the detailed geometric features such as the effect of the pier height on the bending moments or vehicle-pier interaction between the moving vehicles and the PC-I-girder spans. In addition, the model allows one typology to be compared against another, such as slab-versus box girder, in terms of stiffness and vertical displacement. These numerical models are then validated by field data to produce results for structural maintenance and strengthening that are reasonable for decision making. (A. F. Naser & Zonglin, 2010; Yalin, n.d; Wala et al., 2025; Zahid et al., 2020; Rao & Meena, 2017; Adler, 2007).

When the capacity of a bridge is reduced due to any reason, such as ageing, damage, or increased traffic requirements, strengthening is made necessary. One well-established technique is external post-tensioning, in which high-strength steel tendons are inserted outside of the concrete cross-section to create active forces opposing the dead and live loads. Rehabilitation also entails utilizing epoxy concrete to repair weathered surfaces, with the replacement of essential components like the expansion joints and deck pavements. In the case of early design structures such as T-shaped cantilevers or arch bridges, you can upgrade stiffness by external reinforcement or the use of CFRP and still have a proper structural integrity and a significantly increased service life.) (A. F. Naser & Zonglin, 2010; Yalin, n.d.; Wala et al., 2025).

2. Description of the bridge structure

The bridges investigated in this work are prestressed concrete overpass girder bridges located along the Hilla–Kish Expressway in Iraq and assessed in service. They have four spans for a

total length of about 66.5 m and a total width of 9.4 m, including a 7.0 m carriageway and 1.2 m sidewalks on both sides of each bridge. The deck system comprises a reinforced concrete slab cast over precast girders to provide a continuous riding surface, finished with an asphalt wearing course. The superstructure is supported by prestressed U-girders (internal long girders and external short girders), typically arranged as four internal and four external girders per span, with representative girder lengths of about 23.0 m and 10.25 m, respectively. Elastomeric bearings are used at the supports to transfer vertical loads and accommodate rotations. The substructure consists of multi-column reinforced concrete bents (about four columns per bent), with a clear height of 6.75 m from the foundation level to the underside of the superstructure. In addition, reinforced concrete abutments with wing walls retain the approach embankments. The foundation system is formed by reinforced concrete pile caps supported on piles with a diameter of 1.2 m. FIGURE 1 shows the longitudinal section of the bridge.

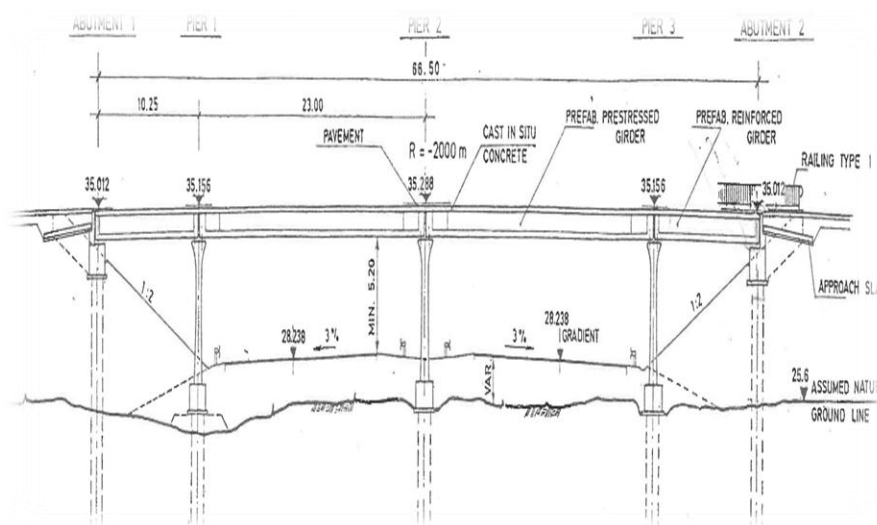


FIGURE 1. Longitudinal section of the bridge.

3. Field static load testing

A static load test was conducted to evaluate the in-service elastic behavior and serviceability of the investigated prestressed concrete (PSC) girder bridges under a controlled loading condition. It consisted of measuring the vertical quasi-static response at strategic locations on the bridge, and the recorded field signals were what enabled the derivation of measurable parameters for practical purposes and structural assessment. The response of the bridge was monitored using high-precision gyroscopic (IMU-based) sensors during the test. The testing program comprised three steps. Firstly, the bridge was measured under dry, unloaded condition, where dummy readings were taken as a reference. Secondly, a known static load was applied by placing two fitted trucks of total weight of about 80 tons at the mid span; it produced a critical flexural demand. Thirdly, the trucks were kept stuck during 20 minutes to stabilize the response taking into account short term time-dependent effects; readings were taken continuously during the loading and truck stabilization. The short term time-dependent effect was isolated by subtraction of loaded readings from the reference readings, and processing of the data revealed key structural indicators. They were bending moments, flexural stresses in the tension and compression reinforcement, vertical displacements, and shear forces. The third step was followed by comparison of the field test results with the calculated plate finite element model output, and served as testing the model for accuracy with reference to an in-service performance. A photograph of the second step measuring is presented in FIGURE 2.



FIGURE 2. The static load test configuration.

4. Experimental static load testing results

The static load test measurements were processed to obtain the maximum response indicators (bending moment, vertical shear, deflection, and flexural stresses) for the three investigated bridges under the combination load case. The following results outcomes as reported in TABLE 1.

Response parameter	Unit	Bridge 1	Bridge 2	Bridge 3
Bending moment +M (positive)	kN·m	947	1045	984
Bending moment -M (negative)	kN·m	-2974	-3306	-3057
Vertical shear (Upward)	kN	2094	2272	2160
Vertical shear (Downward)	kN	-1856	-2157	-1948
Vertical deflection (Upward)	mm	9.20	10.24	9.47
Vertical deflection (Downward)	mm	0	0	0
Top tensile stress (+)	N/mm ²	1.25	1.29	1.17
Top compressive stress (-)	N/mm ²	-0.35	-0.38	-0.35
Bottom tensile stress (+)	N/mm ²	0	0	0
Bottom compressive stress (-)	N/mm ²	-3.38	-3.72	-3.52

TABLE 1. Experimental static load testing results

5. Numerical static load modeling

The numerical static load model was developed using CSI Bridge v26 to represent the bridge system through a three-dimensional finite-element representation which is subjected to service-type static action to simulate the global structural response of the structure. This included an imitation of the real load-transfer system of the superstructure which included the deck and the prestressed girders, and the supporting bearings of restraints. Accordingly, the bridge was conceptualized as a slab-on-girder multi-span system, with both the deck and girders performing as a unit structure for gravity and live load demands. Data. The first stage of model development was geometric definition, which included span configuration, deck parameters, girder spacing, and member section properties of prestressed members. Concrete members were defined with material characteristics that were consistent with the intended configuration of the

structure to accurately represent the stiffness distribution of the superstructure. Composite action between the deck and girders was included to account for the effective flexural participation of the deck in the longitudinal system and thereby providing a sound basis for assessing internal actions and deformations in static loading. Support conditions were defined to reflect the functional behavior of bridge bearings, typically by combining restrained and partially released degrees of freedom to represent hinge and roller-type responses. This idealization allows to transfer longitudinal forces and rotations in a physically meaningful sense while avoiding arbitrary fixity to prevent bending and shear distributions to be incorrectly influenced. The boundary conditions utilized were applied at the ends of the girders and/or at bearing lines based on the span configuration so that the prescribed static response is still realistic.

Static loading was implemented through a structured set of load cases representing permanent and transient effects. Permanent actions included the self-weight of structural components (dead load) and superimposed dead loads such as wearing surfaces. Prestressing actions were modeled as equivalent tendon effects to represent the induced axial force and eccentricity contribution to section response. Live load was applied as a truck-type representation positioned to generate critical effects along the spans. Load combinations were, then, defined identifying all static effects that act simultaneously at the service level, allowing to assess the response quantities of interest under combined action. The static model is trained to predict the numerical outputs that are fundamental response measures that need to be assessed in the structural domain: Reaction forces, longitudinal bending moments (sagging/hogging), vertical shear forces, stress demands at critical fibers of each local prestressed girder section, and vertical deflection profiles across the length of the bridge. These response measures yield a systematic depiction of global static action redistribution and resistance by the bridge system, and serve as the analytical foundation for further interpretation of structural performance in a serviceability focused context.

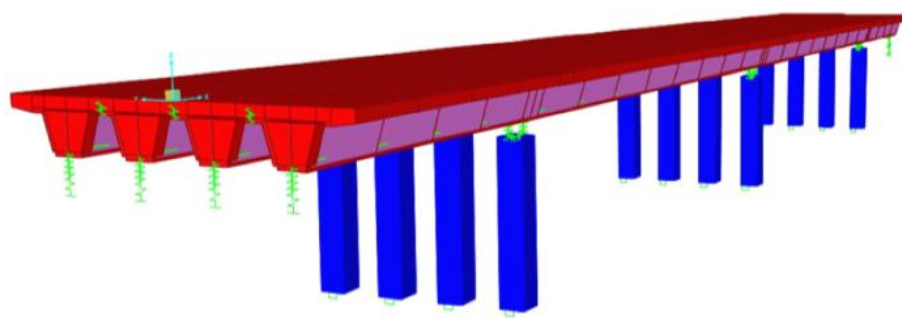


FIGURE 3. 3D view of the bridge.

5.1 Stress analysis :

A. Under the truck (live) load case:

When subjected to moving vehicle loads, the prestressed concrete girders develop a service-level stress condition that is characterized by spans dominated by positive bending, as shown in the contoured stress distribution. The upper fibre stresses are comparatively low, with peak tensile stress of about +0.77 and peak compressive stress of about -0.81 MPa. The response is tensile dominated with an ultimate tensile stress of around +2.00 MPa at the base fibers but the ultimate compressive stress is relatively low at -0.36 MPa. Such a pattern would be expected for girder bridges under live loading as tensile demand tends to develop in the bottom fibers at mid-span locations. In accordance with AASHTO LRFD Bridge Design Specifications, serviceability verification for the investigated bridge (with $f'_c = 45\text{MPa}$ and maximum span

length $L = 23\text{m}$) is performed by comparing computed stresses against prescribed allowable limits. The allowable tensile stress under service conditions is:

$$f_t \leq 0.5\sqrt{f'_c} = 3.35 \text{ MPa} \quad (1)$$

which is intended to control cracking and maintain tensile demands within acceptable bounds. The computed maximum tensile stress under the truck load case (2.00 MPa) is therefore below the allowable tensile limit (3.35 MPa), confirming satisfactory crack-control performance under live loading. Similarly, the allowable compressive stress is restricted to:

$$f_c \leq 0.45f'_c = 20.35 \text{ MPa} \quad (2)$$

to prevent excessive compression that could lead to crushing or long-term deterioration under sustained loading. The computed compressive stresses under truck loading—approximately 0.81 MPa at the top fibers and 0.36 MPa at the bottom fibers in magnitude—are far below the allowable compressive limit (20.35 MPa), indicating an adequate margin of safety against compression-related serviceability concerns.

Overall, the live-load stress envelope demonstrates that the prestressed girders satisfy the AASHTO LRFD service stress criteria, with tensile stresses remaining within the permissible cracking-control threshold and compressive stresses remaining well within the allowable compression limit across the span. FIGURE 4 illustrates the tensile and compressive stress distributions at the top and bottom fibers of the girders due to the truck (live) load case.

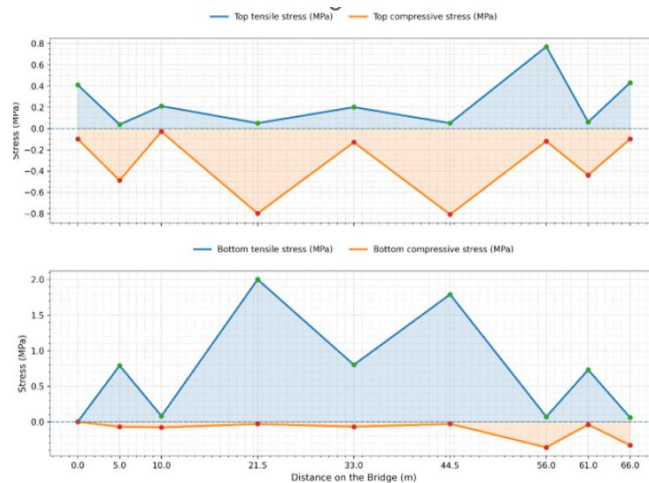


FIGURE 4. Stresses due to the truck (live) load case.

B. Under the combination load case:

The numerical stress distribution shows the super position of gravity action with its counter effect of the prestressing leading to a favorable service-level response along the prestressed concrete girders. However, the peak-fiber stresses are still quite low, the peak tensile stress is less than 1.30 MPa and peak compressive stress is less than -0.40 MPa. The result of the response at the bottom fibers is that tensile stress is virtually zero along the girder and maximum compressive stress of around -4.0 MPa. This verifies that the effects of prestressing fully compensate the tensile stresses due to gravity loads, keeping the highly stressed bottom region in compression within the critical service combination. The calculated tensile and compressive

stresses under interaction loading remain below service stress limits described earlier, ensuring proper cracking control and adequate over-compression margin when compared against adopted limits. Overall, the combination-load stress envelope demonstrates stable service performance of the girders, with tension demands minimized and compression levels remaining moderate across the span. FIGURE 5 presents the tensile and compressive stress distributions at the top and bottom fibers of the girders due to the combination load case.

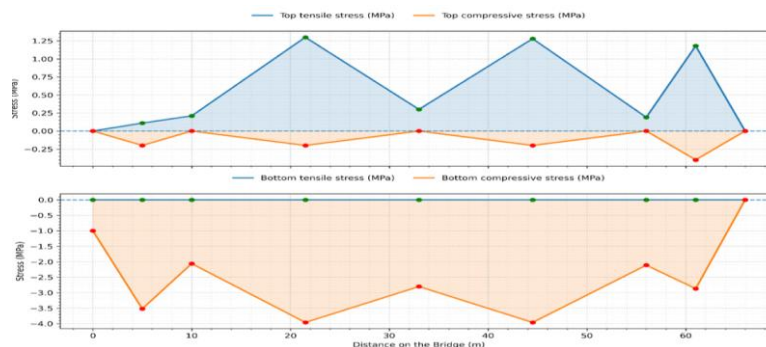


FIGURE 5. Stresses due to the combination load case.

5.2 Vertical deflection analysis:

A. Under the truck (live) load case:

The numerical model shows that the downward deflection (the primary load) caused by gravity of the bridge vertical displacement under the truck (live) load followed the expected deflected shape of a multi-span girder system. In this way, the maximum vertical displacements happen in the span regions whereas the displacement at the support lines is purposely restrained by the bearing conditions. Such a deformation profile is consistent with that of a typical live-load response in which maximum deflections concentrate at the critical loading positions along the spans. To comply with AASHTO LRFD serviceability verification, the deflection under live loading is checked against the limit for maximum vertical displacement.. For the investigated bridge with a maximum span length of $L = 23\text{m}$, the allowable maximum deflection under live load is:

$$\Delta_{max(\text{live load})} \leq \frac{L}{800} = 28.75 \text{ mm} \quad (3)$$

Accordingly, the computed live-load deflection is evaluated relative to this limit to confirm acceptable ride quality and service performance. The numerical results demonstrate that the bridge satisfies the serviceability requirement for vertical displacement under truck loading. FIGURE 6 illustrates the vertical deflection values across the bridge spans, while FIGURE 7 presents the overall view of vertical deflection throughout the bridge spans under the truck (live) load case.

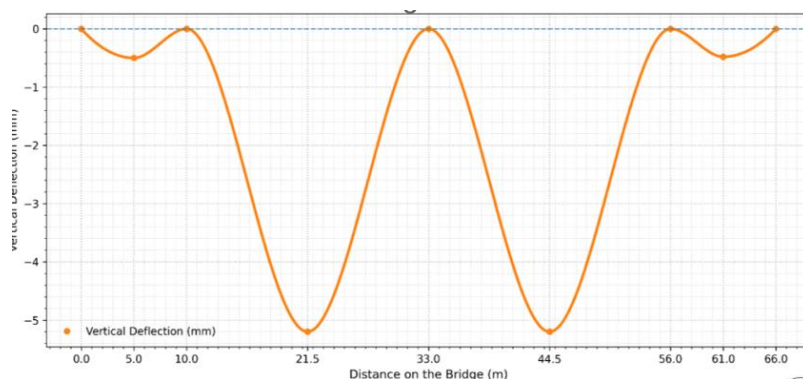


FIGURE 6. The vertical deflection values due to the truck (live) load case

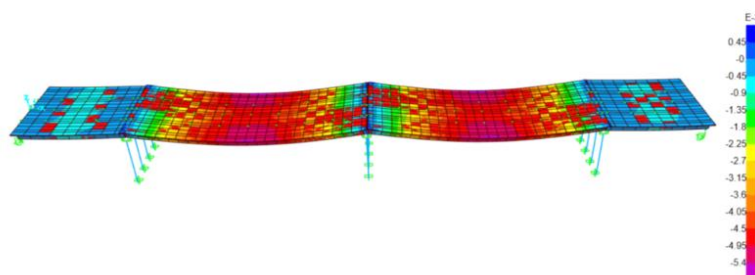


FIGURE 7. Viewing of vertical deflection due to the truck (live) load case.

B. Under the combination load case:

The numerical model shows that the bridge vertical displacement represents the net effect of gravity-induced downward deflection counteracted by the upward camber produced by prestressing. The resulting deflected shape remains consistent with the expected multi-span girder behavior, where maximum vertical displacements occur within the span regions while the displacement at the support lines is essentially restrained by the bearing conditions.

The analysis indicates a maximum vertical deflection under the combination load of approximately 10.58 mm, occurring near $x \approx 44.5$ m, with a close secondary peak of about 10.44 mm near $x \approx 21.5$ m. Minor upward displacements were also observed near the span ends (on the order of 1.38 mm at $x \approx 5.0$ m and 0.69 mm at $x \approx 61.0$ m), reflecting localized dominance of prestressing camber in those regions. Overall, the combination-load displacement profile confirms that prestressing substantially reduces the net downward deflection demand compared to gravity actions alone.

For serviceability verification in accordance with AASHTO LRFD, deflection control is checked against the prescribed limit for combined service effects. For the investigated bridge with a maximum span length of $L = 23$ m, the allowable maximum vertical deflection under the combination load is:

$$\Delta_{max(comb.)} \leq \frac{L}{1200} = 19.16 \text{ mm} \quad (4)$$

Comparing the numerical result (10.58 mm) with the allowable value (19.16 mm) shows that the computed combination-load deflection is within the AASHTO service limit, providing a satisfactory margin. Therefore, the bridge satisfies the serviceability requirement for vertical displacement under the governing combination loading, supporting acceptable ride quality and structural performance during service conditions. Figure 5 illustrates the vertical deflection

values across the bridge spans. Figure 6 depicts the view of vertical deflection throughout the bridge spans.

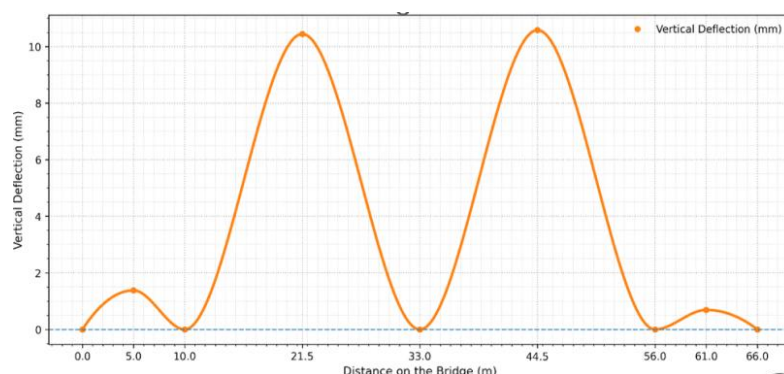


FIGURE 8. The vertical deflection values due to the combination load.

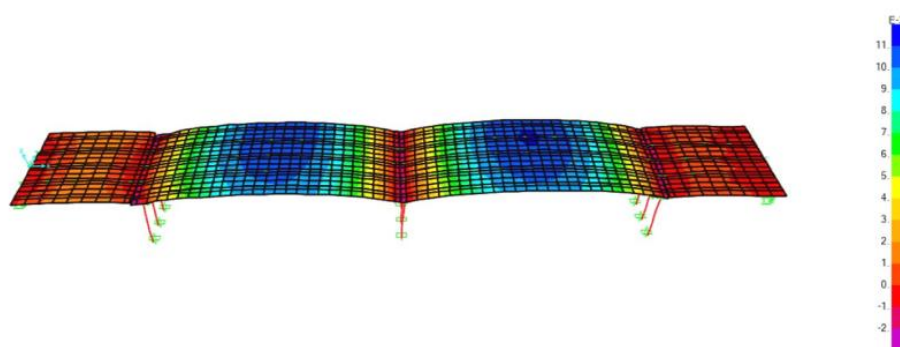


FIGURE 9. Viewing of vertical deflection due to the combination load.

Results

The efficiency coefficient E_c was used to quantify the agreement between the experimental and numerical static-load responses, defined as:

$$E_c = \frac{\text{"Experimental"}}{\text{"Theoretical"}} \quad (5)$$

Values near 1.0 indicate strong agreement of average experimental and numerical responses and values < 1.0 indicate that the measured response is less than that predicted. This is then usually interpreted to imply greater real world rigidity and performance during service. The results of the stress response (considered for the primary service load cases, which were generally the live load and the combination load condition) show that the top-fiber tensile efficiency coefficients ranged from 0.90 to 0.99 (Bridges 1–3: 0.96, 0.99, 0.90), showing that the measured tensile stresses were consistently (but only slightly) lower than the numerical estimates. A similar pattern was noted for top-fiber compressive stresses, further supporting that E_c remained less than unity (0.875–0.95) and confirming that the numerical model conservatively estimate top-fiber compression demand. The efficiency coefficient for tensile stress in the bottom fibers was zero; this was because both the theoretical tensile stress and the experimental tensile stress were zero, meaning the bottom fibers did not remain in tension under the service loads considered—like prestressed girders, in which the tensile force from gravity is balanced by the pre-stressing, reducing the risk for cracking. In the case of bottom-fiber compressive stresses, E_c again remained below unity (0.845–0.93), although the measured compressive stress values were reduced compared to those predicted, indicating a minor reserve in stiffness and load sharing relative to the numerical model.

The same trend was noticed for vertical deflection at the service load cases. The displacement efficiency coefficients were between 0.869 and 0.967 (Bridges 1–3: 0.869, 0.967, 0.895), indicating that the measured deflections (the live-load and combination-load displacement responses depending on the evaluated case) were always less than the theoretical values. This agreement lends support to the stress-based findings and suggest that the as-built bridge system is slightly stiffer than represented in the numerical model, which could be due to modeling idealizations in boundary conditions, composite action representation, and additional stiffness contributions from secondary components.

Conclusion

Field static load testing, in addition to three-dimensional FEM modeling, was used to conduct a structural health assessment of three prestressed concrete overpass bridges straddling the Hilla–Kish Expressway in Iraq. Due to prestressing offsets on the bridges, the tensile stresses that would be caused by gravity are effectively counteracted, leading to low vulnerability of cracking, thus maintaining good structural condition of the bridges. Everything from applied stresses to vertical displacements remained below AASHTO LRFD limits. Importantly, the greatest deflection of 10.58 mm was less than the 19.16 mm threshold, demonstrating appropriate stiffness and ride comfort. Efficiency coefficients between 0.84 and 0.99 indicate a good agreement between field measurements and numerical data, but also suggest that the structures built have some stiffness reserve in their real behavior with respect to the modeled theoretical structures. As such, high-precision IMU measurements coupled with FEM discretization are a cost-effective and sound approach for performing condition and load-carrying capacity evaluation of complex highway infrastructure systems.

Disclosure

The author reports no conflicts of interest in this work

References

- Abad, H., Jaaz, G., Naser, A. F., Mohammed, H. A., & Mohammed, A. A. (2021). Mathematical Modelling of Engineering Problems Earthquake Resistance Optimization and Evaluation of Bridge Piers Structural Form and Dimensions Based on Demand to Capacity Ratio and Yielding Points of Force-Displacement. 8(6), 945–954.
- Adler, S. (2007). The relation between long-term seating comfort and driver movement (Issue September). Friedrich-Schiller-Universitat Jena.
- Ahmed, H., La, H. M., & Gucunski, N. (2020). Review of Non-Destructive Civil Infrastructure. Sensors, 20(3954), 1–38.
- Alampalli, S., & Jalinoos, F. (2009). Use of Nondestructive Evaluation Technologies in the United States Bridge Inspection Practice. 1–14.
- Aliyari, M., Ashrafi, B., & Ayele, Y. Z. (2021). Drone-based bridge inspection in harsh operating environment: Risks and safeguards. International Journal of Transport Development and Integration, 5(2), 118–135. <https://doi.org/10.2495/TDI-V5-N2-118-135>
- Boldrin, P., Fornasari, G., & Rizzo, E. (2024). Review of Ground Penetrating Radar Applications for Bridge Infrastructures. Ndt, 2(1), 53–75. <https://doi.org/10.3390/ndt2010004>
- Bougard, C., Moussay, S., & Davenne, D. (2008). An assessment of the relevance of laboratory and motorcycling tests for investigating time of day and sleep deprivation influences on

- motorcycling performance. *Accident Analysis and Prevention*, 40(2), 635–643. <https://doi.org/10.1016/j.aap.2007.09.002>
- Brinissat, M., Ray, R. P., & Kuti, R. (2024). Evaluation of bridge load capacity using proof-load tests. *IOP Conference Series: Materials Science and Engineering*, 1304(1), 012006. <https://doi.org/10.1088/1757-899x/1304/1/012006>
- Cai, H., Abudayyeh, O., Abdel-Qader, I., Attanayake, U., Barbera, J., & Almaita, E. (2012). Bridge deck load testing using sensors and optical survey equipment. *Advances in Civil Engineering*, 2012. <https://doi.org/10.1155/2012/493983>
- Chavel, B. W. (2012). *Steel bridge design handbook: Bridge deck design*. United States. Federal Highway Administration. Office of Bridge Technology.
- Döring, T., Kern, D., Marshall, P., Pfeiffer, M., Schöning, J., Gruhn, V., & Schmidt, A. (2011). Gestural interaction on the steering wheel. *Proceedings of the 2011 Annual Conference on Human Factors in Computing Systems*, 483. <https://doi.org/10.1145/1978942.1979010>
- Freddi, F. (2023). *Operational Modal Analysis on Bridges : A Comprehensive Review*.
- Garnica, G. I. Z., Zhang, F., Yang, Y., van der Veen, C., Lantsoght, E. O. L., Naaktgeboren, M., & Fennis, S. A. A. M. (2021). Monitoring structural responses during proof load testing of reinforced concrete bridges: A review. *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations - Proceedings of the 10th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2020, March*, 2339–2346. <https://doi.org/10.1201/9780429279119-319>
- Gatesi, J. D. D., Chingui, J. A., & Botir, E. (2020). A Review of Bridge Management System: Deterioration Models. *Asian Journal of Engineering and Technology*, 8(2), 55–62. <https://doi.org/10.24203/ajet.v8i2.6263>
- Hasani Hamed, & Francesco Freddi. (2023). *Operational Modal Analysis on Bridges: A Comprehensive Review*. *Infrastructures*. <https://doi.org/10.3390/infrastructures8120172>
- Iacovino, C., Turksezer, Z. I., Giordano, P. F., & Li, M. P. (2022). A Survey of Bridge Condition Rating Systems A survey of bridge condition rating systems. January. <https://doi.org/10.1007/978-3-030-91877-4>
- Kee, S.-H., Oh, T., Popovics, J. S., Arndt, R. W., & Zhu, J. (2012). Nondestructive Bridge Deck Testing with Air-Coupled Impact-Echo and Infrared Thermography. *Journal of Bridge Engineering*, 17(6), 928–939. [https://doi.org/10.1061/\(asce\)be.1943-5592.0000350](https://doi.org/10.1061/(asce)be.1943-5592.0000350)
- Kolhe, S. S., & Shiyekar, M. R. (2023). *Structural Behaviour of Curved Box Girder Bridge*. www.irjet.net
- Komarizadehasl, S., Huguenet, P., Lozano, F., Lozano-Galant, J. A., & Turmo, J. (2022). Operational and Analytical Modal Analysis of a Bridge Using Low-Cost Wireless Arduino-Based Accelerometers. *Sensors*, 22(24). <https://doi.org/10.3390/s22249808>
- Kumar, M., Ghorpade, V., & Rao, H. (2018). Analysis and Design of Stress Ribbon Bridge with CSI Bridge Software. *International Journal of Civil Engineering and Technology (IJCIET)*, 9(10), 1532–1544. <http://iaeme.com/http://iaeme.com/Home/journal/IJCIET1533http://iaeme.com>
- Kumar, M. H. (2018). ANALYSIS AND DESIGN OF STRESS RIBBON. 9(10), 1532–1544.
- Landge, S., Bhagat, U., Bhaisare, S., Prakash, V., & Khedikar, I. P. (2018). *Analysis and Design*

of Pre-stressed Concrete I-Girder Bridge.

- Lantsoght, E. (2023). Proof Load Testing Method by the American Association of State Highway and Transportation Officials and Suggestions for Improvement. May. <https://doi.org/10.1177/03611981231165026>
- Liu, X. (2026). Advances in Civil Engineering Reliability Assessment of Simply Supported Beam Bridge Structural Performance Based on Load Tests. 1–15. <https://doi.org/10.1155/adce/7942715>
- Mrv, P. (2020). Seismic Performance of Box Girder Bridge with Non-Linear Static Pushover. March.
- Mohammed, H. A., & Naser, A. L. I. F. (2020). MATHEMATICAL ASSESSMENT OF VEHICLES TYPES AND LOADS INFLUENCES ON THE STRUCTURAL PERFORMANCE PARAMETERS OF CONCRETE AND STEEL BRIDGES. 15(2), 1254–1266.
- Mohseni, I., Lashkariani, H. A., Kang, J., & Kang, T. H. K. (2018). Dynamic response evaluation of long-span reinforced arch bridges subjected to near- and far-field ground motions. Applied Sciences (Switzerland), 8(8). <https://doi.org/10.3390/app8081243>
- Naser, A. F. (2018). OPTIMUM DESIGN OF VERTICAL STEEL TENDONS PROFILE LAYOUT OF POST-TENSIONING CONCRETE BRIDGES: FEM STATIC ANALYSIS. 13(23), 9244–9256.
- NASER, A. F. (2021). Analysis the effect of super-elevation on static and dynamic properties of horizontal curved concrete bridge by finite element. Journal of Engineering Science and Technology, 16(5), 3669–3686.
- Naser, A. F., Mohammed, H. A., & Mohammed, A. A. (2021). Mathematical Modelling of Engineering Problems Mathematical Modeling of Linear Static and Dynamic Analysis for Pier Height Effect on the Structural Performance of Bridges Structures. 8(4), 617–625.
- Naser, A. F., & Wang, Z. (2011). Field damage inspection and static load test analysis of Jiamusi highway prestressed concrete bridge in China. Advanced Materials Research, 163–167(December 2010), 1147–1156. <https://doi.org/10.4028/www.scientific.net/AMR.163-167.1147>
- Naser, A. F., & Zonglin, W. (2010). STRENGTHENING OF JIAMUSI PRE-STRESSED CONCRETE HIGHWAY BRIDGE BY USING EXTERNAL POST-TENSIONING TECHNOLOGY IN CHINA. 5(11), 60–69.
- Naser, A. L. I. F., & Zonglin, W. (2011). Procedia Engineering Damage Investigation , Strengthening , and Repair of Jilin Highway Double-Curved Arch Concrete Bridge in China. <https://doi.org/10.1016/j.proeng.2011.07.289>
- Ni, X., Leon-miquel, M., Greiner, Q. R., Paul, A., & Jin, Q. (2023). Crack sealers for the preservation of concrete bridge decks : a synthesis of a national survey and literature review. 8.
- Nowotarski, P., Dubas, S., & Milwicz, R. (2017). Review of the Air-Coupled Impact-Echo Method for Non-Destructive Testing. IOP Conference Series: Materials Science and Engineering, 245(3), 0–10. <https://doi.org/10.1088/1757-899X/245/3/032098>
- Panigati, T., Zini, M., Striccoli, D., Francesco, P., Tonelli, D., Pina, M., & Zonta, D. (2025).

- Drone-based bridge inspections : Current practices and future directions Automation in Construction Drone-based bridge inspections : Current practices and future directions. Automation in Construction, 173(May), 106101. <https://doi.org/10.1016/j.autcon.2025.106101>
- Rao, N. V., & Meena, T. (2017). A review on carbonation study in concrete. IOP Conference Series: Materials Science and Engineering, 263(3). <https://doi.org/10.1088/1757-899X/263/3/032011>
- Ritter, M. A. (1990). Timber bridges: Design, construction, inspection, and maintenance. US Department of Agriculture, Forest Service, Engineering Staff.
- Ryan, T. W., Lloyd, C. E., Pichura, M. S., Tarasovich, D. M., & Fitzgerald, S. (2022). Bridge inspector's reference manual (BIRM). National Highway Institute (US).
- Singh, N., & Maru, D. S. (2023). Seismic Behaviour PSC Box Girder and PSC Precast I Girder Bridge. International Journal for Research in Applied Science and Engineering Technology, 11(3), 1576–1583. <https://doi.org/10.22214/ijraset.2023.49738>
- Spencer, B. F., Hoskere, V., & Narazaki, Y. (2019). Advances in Computer Vision-Based Civil Infrastructure Inspection and Monitoring. Engineering, 5(2), 199–222. <https://doi.org/10.1016/j.eng.2018.11.030>
- Structures, E. (2015). Inspection survey of 150 expansion joints in road bridges. July. <https://doi.org/10.1016/j.engstruct.2009.01.011>
- Sun, S., Lei, G., & Sun, Z. (2019). Mathematical Modelling of Engineering Problems Dynamic and Static Load Tests on a Large-span Rigid-frame Bridge. 6(3), 409–414.
- Terranova, B., Shafieezadeh, A., & DesRoches, R. (2012). Analytical fragility assessment of an isolated multi-span simply supported concrete girder bridge in moderate seismic zones. Università degli Studi di Pavia.
- Tu, K., Ye, Y., Wu, D., Zhou, Y., & Deng, W. (2023). Technical Analysis of Highway Bridge Static Load Test. 7(3), 58–63.
- Vardanega, P. J., Tryfonas, T., Gavriel, G., Nepomuceno, D. T., Pregolato, M., & Bennetts, J. (2024). A review of recent research on visual inspection processes for bridges and the potential uses of AI. Bridge Maintenance, Safety, Management, Digitalization and Sustainability, 3573–3580.
- Wala, A., Naser, A. F., Aldhalemi, A. A., & Mahmood, H. F. (2025). International Journal of Transport Development and Integration Damages Inspection and Finite Element Model Analysis of Static and Dynamic Factors of Steel Girder-Concrete Composite Span Due to Vehicles Live Load and Loads Combination. 9(1), 151–162.
- Wang, X., Yang, Q., & Peng, X. (2024). A Review of Concrete Carbonation Depth Evaluation Models.
- Xu, G., Ph, D., & Azhari, F. (2025). Bridge Maintenance Management Based on Routine Inspection Data : A Bridge Maintenance Management Based on Routine Inspection Data : A Quantitative Approach. November 2024. <https://doi.org/10.1061/JBENF2.BEENG-6685>
- Yalin, Y. (n.d.). Rationality Analysis of Continual Improvement of a Simply Supported T Beam Bridge Rationality Analysis of Continual Improvement of a Simply Supported T Beam Bridge. <https://doi.org/10.1088/1755-1315/304/3/032103>

- You, A., Be, M., & In, I. (2025a). Dynamic and Modal Responses Evaluation of Precast. September 2023.
- You, A., Be, M., & In, I. (2025b). Dynamic structural performance evaluation of simply supported precast prestressed concrete I-girder bridge □. 080023(May).
- Zahid, F. Bin, Ong, Z. C., & Khoo, S. Y. (2020). A review of operational modal analysis techniques for in - service modal identification. Journal of the Brazilian Society of Mechanical Sciences and Engineering, August. <https://doi.org/10.1007/s40430-020-02470-8>
- Zhang, C., Zou, Y., Wang, F., del Rey Castillo, E., Dimyadi, J., & Chen, L. (2022). Towards fully automated unmanned aerial vehicle-enabled bridge inspection: Where are we at? Construction and Building Materials, 347(October). <https://doi.org/10.1016/j.conbuildmat.2022.128543>