Link Slab Behavior in Continuous Bridge Systems: A Comparative Study of Finite Element and Analytical Approach

Made Suangga
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia
suangga@binus.ac.id

Olivia Megasari
Civil Engineering Department, Faculty of Engineering, Tarumanagara University, Jakarta, Indonesia
olivia.megasari@untar.ac.id

Riza Suwondo
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia
riza.suwondo@binus.ac.id (corresponding author)

Received: 30 June 2024 | Revised: 26 July 2024 | Accepted: 28 July 2024

DOI: https://doi.org/10.48084/etasr.8267

ABSTRACT

Performance and longevity of bridge structures are usually compromised by the use of expansion joints, which are prone to material deterioration and are costly to maintain. To address these drawbacks, partially continuous systems with link slabs are increasingly adopted. This study aims to provide a detailed understanding of the behavior of link slabs. A numerical model was developed using finite element analysis to simulate the behavior of the link slabs. The results of the model were compared to those of the analytical solution. The study also examined the effects of various parameters, including the Debonding Length Ratio (DLR) and the span length on link slab performance. The results indicate that the numerical model tends to overpredict the link-slab rotations when compared to the analytical solution. However, the moments in the link slab showed a decrease with increasing span length in the numerical analysis, contrary to the analytical solution which indicated an increase. In addition, higher DLRs resulted in reduced rotations and increased moments in the numerical model, whereas the analytical solution showed no effect on rotation and a decrease in moments with higher DLR. These results highlight the necessity of using detailed numerical models to accurately analyze and optimize the design of link slabs.

Keywords-link slab; partial continuous bridge systems; finite element analysis; debonding length ratio; structural behavior

I. INTRODUCTION

Over the past several decades, simply supported systems have been widely utilized in bridge construction, due to their straightforward implementation. These systems require the use of expansion joints to connect the adjacent bridge decks. However, the inclusion of expansion joints is associated with numerous issues including material deterioration and high maintenance costs [1-3]. The adverse effects of the expansion joints on the long-term performance and service life of bridges have been extensively documented [4-6]. To address these drawbacks, partially continuous systems incorporating link slabs have been increasingly adopted in bridge engineering [7-9]. In these systems, bridge decks are connected to one another, whereas the girders remain separate, as illustrated in Figure 1. This configuration offers a balance of simplicity and efficiency compared to fully continuous systems. The link slabs serve as replacements of the deck expansion joints, particularly in short- and medium-length multi-span bridges. They are segments of the bridge deck positioned over the joints, linking two adjacent deck spans and allowing the deck to behave as a continuous structure. The girders continue to function as simply supported elements. This design approach mitigates issues associated with traditional expansion joints, such as material deterioration and maintenance costs, by eliminating joints and providing a seamless transition between spans. The use of link slabs not only enhances the durability of the bridge by reducing the ingress of water and debris but also simplifies the maintenance process. Additionally, the continuous nature of the deck improves the load distribution and reduces stress concentrations, potentially leading to longer service life and lower lifecycle costs. Recent studies have highlighted the effectiveness of link slabs in improving the overall performance and reliability of bridge structures, thereby making them viable alternatives to conventional expansion joints.

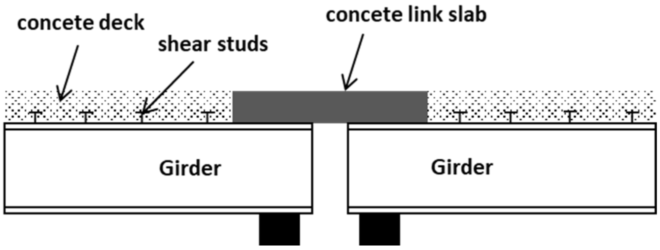

Fig. 1. Link slab connecting two girders.

The application of link slabs in bridge construction has been investigated extensively. Authors in [10, 11] emphasized the advantages of link slabs, such as reduced maintenance costs and enhanced seismic performance. Authors in [12] provided a detailed examination of the structural behavior of bonded link slabs, highlighting their critical role in ensuring continuity within bridge systems. Authors in [13] introduced an innovative transition zone design for bridge deck link slabs, incorporating ductile concrete to prevent interfacial cracking and enhance load transfer. Collectively, these studies underscore the significant potential of link slabs in improving the performance and durability of continuous bridge structures.

Authors in [14] developed a finite element model to analyze jointless bridge decks with simple span girders. Nonlinear material effects such as cracking, thermal expansion, creep, and shrinkage were considered. However, the finite element model results did not agree well with the experimental findings. In [15] this approach was advanced by incorporating partial debonding into a deck. Authors in [16] conducted an experimental study to assess the performance of jointless bridge decks. Their research demonstrated that a link slab experiences bending under traffic loads, rather than axial elongation. Observations indicated that cracks formed at the top of the link slab due to negative bending moments. To mitigate this issue, they recommended debonding of the link slab over the girder joint for a length of 5% of each girder span. This reduction in the link slab stiffness can be applied to both new and existing bridge decks to improve their overall performance and durability. Authors in [17] examined the performance of link slabs on 468 bridges in Texas. This study used as-built drawings and inspection reports to document the design characteristics and damage conditions of these bridges. A damage rating system was developed to evaluate the performance of the link slabs on each bridge. The correlation between various bridge design characteristics and the link slab performance were assessed. The results indicated that factors such as continuous deck length and mean span length were significantly correlated with the performance of the link slabs. Author in [18] developed Finite Element (FE) models to analyze the variations in forces, stresses, and moments within link slabs, as well as the level of continuity achieved in the girder system. The analysis considered various bridge parameters that are likely to influence link slab behavior, such as bearing stiffness, skew angle, span lengths, and Debonding Length Ratio (DLR). The results indicated that with an increase in the bearing stiffness and DLR, the link slab exhibited behavior more characteristic of a tensile member than of a bending member. This observation was consistent across all the evaluated bridge types and skew angles.

Despite the mentioned abovese valuable contributions, there still is a significant research gap in understanding the detailed behavior of link slabs, particularly concerning their rotation and moment responses under varying debonding length ratios and span lengths. The previous studies have not thoroughly addressed the combined effects of these parameters on the performance of the link slabs. The primary objective of this study is to address the existing gap in understanding the behavior of link slabs in bridge structures, with the ultimate goal of providing informed design recommendations. To achieve this, a detailed numerical model using Finite Element Analysis (FEA) was developed to simulate the behavior of the link slabs under various conditions. The results obtained from the FEA were systematically compared with the analytical solutions to validate the model. Additionally, a series of parametric analyses were conducted to investigate the influence of key factors such as the DLR and the span length on the behavior of link slabs, aiming to identify critical parameters that affect the performance and structural integrity of link slabs, thereby contributing to the development of optimized design guidelines for partial continuous bridge systems.

II. METHODOLOGY

Figure 2 shows the methodology flowchart of this research. The process begins by defining the research objectives and key parameters, followed by the development of a numerical model using SAP 2000, which includes discretising slabs and modelling girders. Various parameters, such as the span length and the DLR were set up and the model was validated against analytical solutions. Simulations were performed under specified load scenarios, and the results were analyzed regarding moments, rotations, and stresses. The findings were compared with analytical solutions to interpret behavioral differences and to be used to provide optimized design recommendations for link slabs in bridge construction.

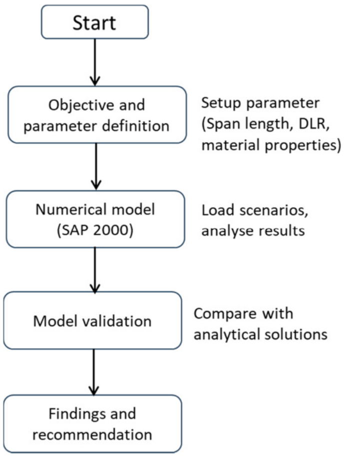

Fig. 2. Methodology flow chart

In this study, a precast prestressed I-girder bridge system was analysed. The bridge comprised two spans of equal length with a skew angle of 0°, as shown in Figure 3. The thickness of both the link slab and the main slab was 20 cm, and the distance between the girders was 1.85 m. Three span lengths were considered: 26 m, 32 m, and 40 m. Specific precast I-girder sections were used for different span lengths, as illustrated in Figure 4.

- For the 26 m span, an H-140 I section was used.
- For the 32 m span, an H-170 I section was used.
- For the 40 m span, an H-210 I section was used.

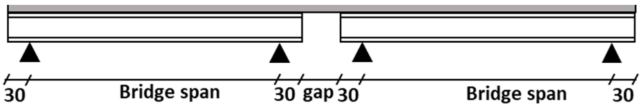

Fig. 3. The selected bridge

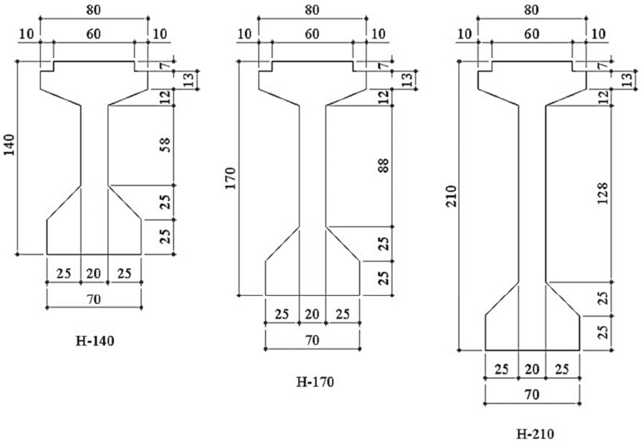

Fig. 4. The prestressed I girder section

The debonding length of the link slab was set as 5% of the span length. The materials used were K-600 (fc' 50 MPa) concrete for the girders, and K-350 (fc' 30 MPa) concrete for the slabs. The Poisson's ratio and thermal expansion coefficient of the concrete are 0.2 and 10×10^{-5} /°C, respectively. Reinforcement was provided by 16-mm diameter bars, placed at 125-mm centre-to-centre spacing, with a yield strength of 400 MPa.

A numerical model was developed using the finite element software SAP 2000 [19]. The slab and link slab were discretised using shell elements with both the membrane and bending stiffness. The widths of the slab and link slab were considered as the effective widths of the girder. An uncracked section of the slab was considered in this study. Based on the recommendations of Caner and Zia, a reduction factor of 0.4 was applied to the stiffness inertia of the link slab. A maximum mesh size of 0.3 m was adopted to achieve the desired level of accuracy.

The girder, including its flanges and web, was modelled using frame elements with axial and bending stiffness. Notably, the web and flange were modelled as a single element because transverse bending stiffness was not considered in this study. A rigid link utilising joint constraints was employed to model the connection between the flange and deck, as illustrated in Figure 5. This rigid link provided displacement restraints while allowing free rotation. As depicted in Figure 4b, the joint constraint numbers are defined as the nodes connecting the shell and frame elements, with each shear connector represented by a joint constraint.

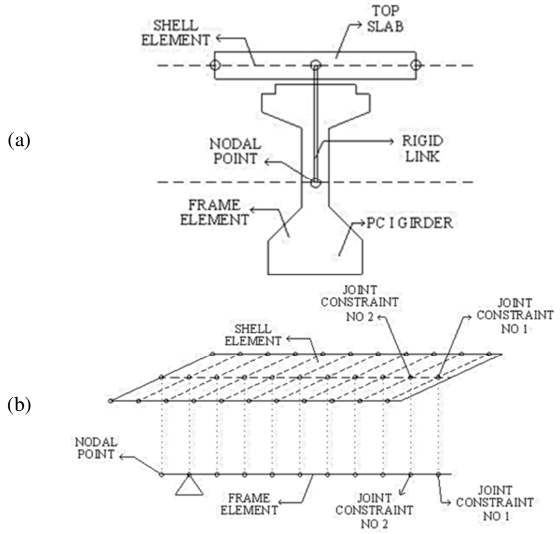

Fig. 5. Link slab modelling approach: (a) cross section, (b) longitudinal section.

Rigid links were not applied in the debonding length zone and joint constraints were not assigned to the shell and frame elements, as shown in Figure 6. A series of load scenarios were considered, as illustrated in Figure 7. The analysis considered the combined effects of these loads on the link slab and girder system, ensuring a thorough understanding of their interactions and the resulting rotations and moments. Figure 8 shows the output obtained from the numerical model.

The results from the numerical model were then compared with those of the analytical method which involves deriving solutions using mathematical formulations and simplified assumptions to represent the physical behavior of structures. This method assumes that the debonding length results in two consecutive beams, which can be modelled independently as simple beams. The loads considered in this analysis are of two types: dead and live loads from vehicular traffic. Calculations using this method utilize the operating-limit condition.

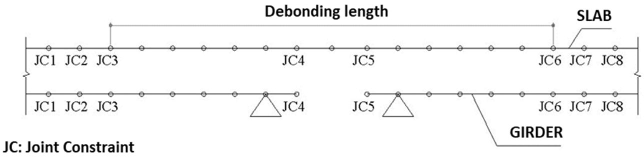

Fig. 6. Link slab modeling at the debonding length zone.

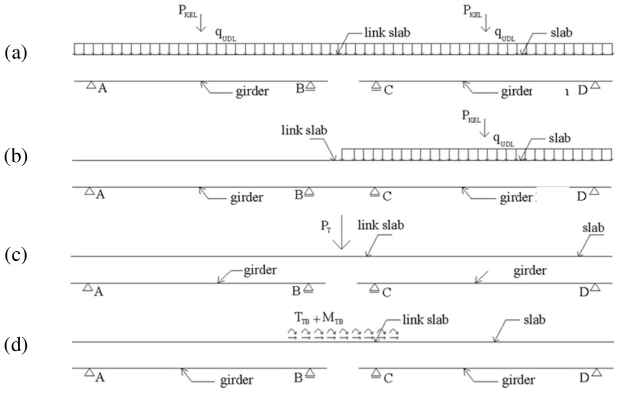

Fig. 7. Load scenarios: (a) live load applied at two spans, (b) live load applied at only one span, (c) live loadapplied at the sink slab, and (f) breaking load applied at the link slab.

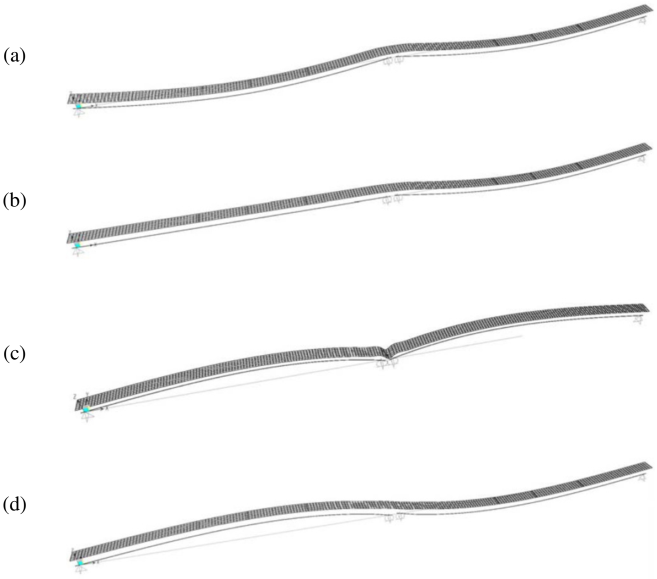

Fig. 8. SAP 2000 output: (a) live load applied at two spans, (b) live load applied at only one span, (c) live loadapplied at the sink slab, and (f) breaking load applied at the link slab.

III. RESULTS AND DISCUSSION

This section presents the behavior of the link slab as determined using a previously described numerical method. The FEA results were compared with the analytical solution developed in [16]. The comparison includes an examination of key parameters such as rotation and moment. In addition, the influence of various factors, including the debonding length ratio and the span length, on the behavior of the link slab was analyzed. The discussion highlights the discrepancies between the numerical and analytical results, provides possible explanations for these differences, and offers insights into the practical implications for bridge design and performance.

Figure 9 shows the link-slab rotation for different span lengths. Both the numerical method results and analytical solution indicate an increase in rotation with span length, which is attributed to the increasing tributary load on the link slab. In general, the numerical analysis overpredicted slightly the rotation compared to the analytical solution. Despite this prediction, the rotations obtained from both methods remained within the acceptable limits. A detailed examination of the results reveals that the numerical model tends to produce higher rotation values, which may exist due to the inherent assumptions and approximations in the FE model. These include discretisation of the slab and application of boundary conditions. Conversely, the analytical solution proposed in [16] provides a simplified approach that potentially underestimates certain complex interactions within a bridge system. Figure 10 shows the moments at different span lengths. The results indicate that the moments obtained from the numerical analysis decreased as the span length increased. Conversely, the moments derived from the analytical solution increased with longer spans. This divergence in the results between the numerical analysis and the analytical solution can be attributed to several factors. In the numerical model, the reduction in moments with increasing span length may be due to the redistribution of stresses and the influence of boundary conditions, which are more accurately captured in finite element analysis. The model likely accounts for the flexibility and continuity of the bridge deck, leading to a more efficient distribution of loads, and consequently, lower moments.

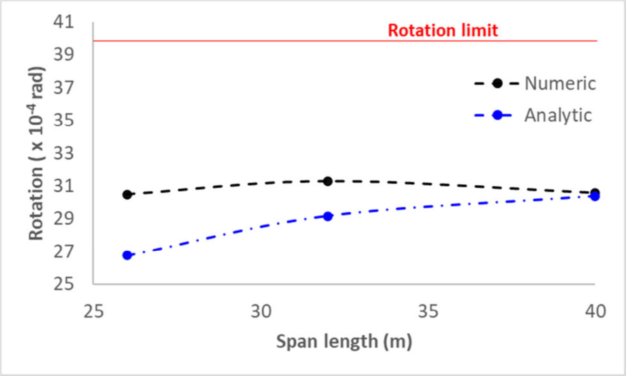

Fig. 9. The link rotation at different span lengths.

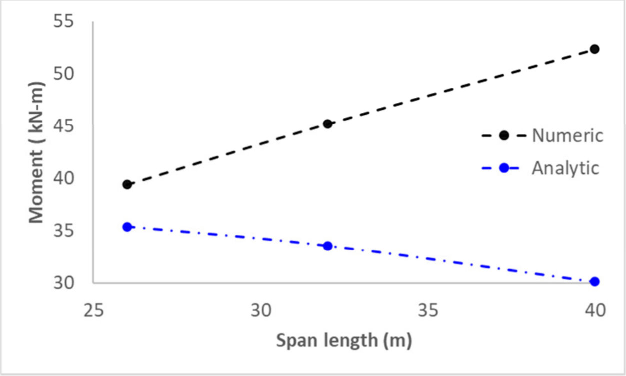

Fig. 10. The moments at different span lengths.

However, the analytical solution simplifies many of these interactions and may assume a more rigid behavior, leading to higher calculated moments with increased span lengths. The analytical approach may not fully capture the complex interactions and load redistributions occurring over longer spans, resulting in an overestimation of the moments. The discrepancy between the numerical and analytical results highlights the importance of choosing an appropriate method for analysing different aspects of bridge behavior. While the analytical solution provides a quick and useful approximation, it may not fully encompass the detailed behaviours observed in a comprehensive numerical model.

Figure 11 shows the effect of the DLR on the moment at the link slab. The numerical analysis indicated that the moment increased as the DLR increased. In contrast, the analytical solution shows a decrease in the moment with increasing DLR.

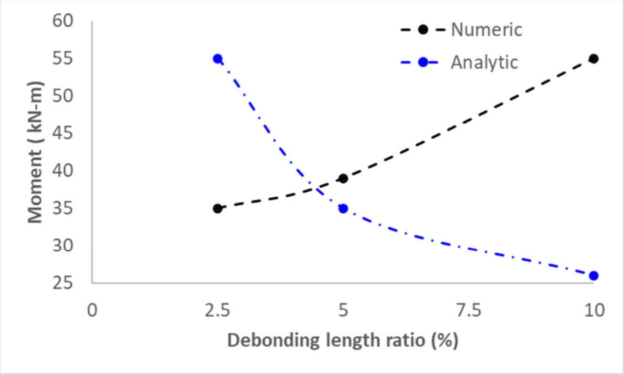

Fig. 11. The moments for different DLR values.

The disparity between the analytical and numerical results can be explained by the inherent differences in how each method models the behavior of the link slab. The analytical approach is simpler and does not account for the detailed deformation mechanics and stress redistributions that occur in the presence of varying DLRs. In contrast, the FE model captures these complexities, revealing how an increased debonding length enhances the flexibility and deformation capacity of the link slab, thereby reducing the rotational effects.

Table I summarizes the differences between the numerical model and the analytical solution. The findings of this study have significant practical implications for the design and maintenance of bridges.

TABLE I. NUMERICAL AND ANALYTICAL RESULTS

Span	**Rotation (×10^4 rad)**		**Moment (kN/m)**	
	Numerical	**Analytical**	**Numerical**	**Analytical**
26	30.49	26.75	39.4	35.4
32	31.29	29.17	45.2	33.57
40	30.58	30.37	52.32	30.13
DLR	**Rotation (× 10^4 rad)**		**Moment (kN/m)**	
	Numerical	**Analytical**	**Numerical**	**Analytical**
26	36.3	31.8	35	55
32	36.1	31.8	39	35
40	34.6	31.8	55	26

The results suggest that increasing the debonding length can effectively manage rotations, thus enhancing the structural flexibility and lifespan of the link slabs. Additionally, understanding the different responses of moments in the analytical and numerical solutions can guide more accurate and resilient bridge designs. Implementing these insights can lead to reduced maintenance costs, as cracking and other deterioration forms are less likely to occur to optimized link slabs. Overall, the outcomes of this study provide valuable guidelines for designing more durable and cost-effective bridge structures with link slabs.

IV. CONCLUSIONS

This study aims to address the lack of a detailed understanding of the behavior of link slabs in partial continuous bridge systems. By employing a finite element model developed in SAP2000, this study simulated the behavior of link slabs and compared the results with analytical the solutions. Several findings emerged from this analysis, providing valuable insights into bridge design and performance optimisation.

- Link slab rotation: The numerical model showed that link slab rotation increased with span length, which aligns with the analytical solution of the authors of [16] who also observed increased rotation with longer spans. However, the numerical analysis slightly over-predicts rotations in comparison with the their experimental data, indicating that the model captures more detailed structural behaviors.
- Moments in the link slab: Contrary to the analytical solution, which shows an increase in moment with span length, the numerical analysis indicates a decrease in the moment. This difference highlights the limitations of traditional analytical methods and underscores the advanced capabilities of the proposed numerical model in capturing complex behaviors. The findings on moment reduction with span length differ from those of the authors in [16] who reported increasing moments, thereby demonstrating the novelty and depth of the numerical approach.
- Effect of DLR on rotation: While the analytical solution showed no effect of DLR on rotation, the numerical analysis revealed that increased DLR reduced rotation due to the larger deformation areas. This observation is consistent with that of [12] in which it was noted that debonding affects link slab flexibility. However, this study provides a more nuanced understanding of the quantitative impacts of DLR variations.
- Effect of DLR on moment: The numerical results indicate that the moment increases with a higher DLR, while the analytical solution shows a decrease. This discrepancy underscores the necessity of using sophisticated numerical models [15, 18]. However, this study extends these findings by providing detailed parametric insights.
- Design Implications: The results of this study emphasize the necessity of integrating both numerical and analytical methods in bridge design to achieve a comprehensive understanding of link slab behavior. While analytical solutions offer valuable baseline estimates, numerical models provide detailed insights that are crucial for optimizing design and ensuring structural integrity.

In conclusion, this study highlights the intricate behavior of link slabs in partially continuous bridge systems. The findings suggest that higher debonding length ratios, while beneficial in reducing rotations, can increase moments, necessitating careful consideration in the design. The discrepancies between the numerical and analytical results reinforce the need for a detailed numerical analysis to capture the full range of structural behavior. These insights can lead to better design practices and ultimately enhance safety, durability, and performance of continuous bridges.

Future research should continue to explore complex interactions within link slabs under various loading conditions and bridge configurations. Such studies will further refine the design recommendations and contribute to the development of more resilient and cost-effective bridge structures

ACKNOWLEDGMENT

The authors express sincere gratitude to the Karbonara Research Institute for their invaluable support and resources provided throughout this research. Special thanks are extended to the Civil Engineering Department of BINUS University for their continuous guidance, encouragement, and access to the necessary facilities and equipment.

DATA AVAILABILITY

Data Analysis of Link Slab Behavior in Continuous Bridge Systems https://zenodo.org/records/13138904

REFERENCES

[1] H. Ngo, I. Steele, and N. Lake, *Design rules for bridge bearings and expansion joints*. Sydney, NSW, Australia: Austroads, 2012.

[2] D. Mohammed and S. R. Al-Zaidee, "Deflection Reliability Analysis for Composite Steel Bridges," *Engineering, Technology & Applied Science Research*, vol. 12, no. 5, pp. 9155–9159, Oct. 2022, https://doi.org/10.48084/etasr.5146.

[3] K. M. Wing and M. J. Kowalsky, "Behavior, Analysis, and Design of an Instrumented Link Slab Bridge," *Journal of Bridge Engineering*, vol. 10, no. 3, pp. 331–344, May 2005, https://doi.org/10.1061/(ASCE)1084-0702(2005)10:3(331).

[4] M. P. Burke, "Flawed Assumptions and the Failure of Bridge Deck Jints and Bearings," in *Fourth World Congress on Joint Sealants and Bearing Systems for Concrete Structures*, Sacramento, CA, USA, Oct. 1996, vol. 164, pp. 59–80, https://doi.org/10.14359/1435.

[5] C. Shi, R. Zhao, W. Wang, and S. Zhang, "Effect of load on bonding properties and salt freeze-thaw resistance of bridge expansion joint concrete," *Construction and Building Materials*, vol. 411, Jan. 2024, Art. no. 134680, https://doi.org/10.1016/j.conbuildmat.2023.134680.

[6] Y. Ma, A. Peng, L. Wang, C. Zhang, J. Li, and J. Zhang, "Fatigue performance of an innovative shallow-buried modular bridge expansion joint," *Engineering Structures*, vol. 221, Oct. 2020, Art. no. 111107, https://doi.org/10.1016/j.engstruct.2020.111107.

[7] C. L. Loveall, "Jointless bridge decks," *Civil Engineering*, vol. 55, no. 11, pp. 64–67, Nov. 1985.

[8] L. Zhang *et al.*, "Structural performance evaluation of ECC link slabs reinforced with FRP bars for jointless bridge decks," *Construction and Building Materials*, vol. 304, Oct. 2021, Art. no. 124462, https://doi.org/10.1016/j.conbuildmat.2021.124462.

[9] Y. Bi *et al.*, "Theoretical and finite element analysis of engineered cementitious composite (ECC) link slab in hollow slab beam bridge base on different load conditions," *Engineering Structures*, vol. 308, Jun. 2024, Art. no. 118045, https://doi.org/10.1016/j.engstruct.2024.118045.

[10] A. Mostafa, L. Radwan, A. Elmanney, and A. Gadellah, "Review Paper on Link Slab Bridge Girder Technique," *International Journal of Engineering Research*, vol. 9, no. 9, pp. 535–542, 2020.

[11] A. Caner, E. Dogan, and P. Zia, "Seismic Performance of Multisimple-Span Bridges Retrofitted with Link Slabs," *Journal of Bridge Engineering*, vol. 7, no. 2, pp. 85–93, Mar. 2002, https://doi.org/10.1061/(ASCE)1084-0702(2002)7:2(85).

[12] A. N. Gergess and E. Z. Douaihy, "Effects of Elastomeric Bearing Stiffness on the Structural Behavior of Bonded Link-Slabs," *Transportation Research Record*, vol. 2674, no. 4, pp. 428–443, Apr. 2020, https://doi.org/10.1177/0361198120911046.

[13] S. Qian, M. D. Lepech, Y. Y. Kim, and V. C. Li, "Introduction of Transition Zone Design for Bridge Deck Link Slabs Using Ductile Concrete," *ACI Structural Journal*, vol. 106, no. 1, pp. 96–105, Jan. 2009, https://doi.org/10.14359/56288.

[14] F. Gastal and P. Zia, "Analysis of bridge beams with jointless decks," in *Durability Of Structures, IABSE Symposium*, Lisbon, Portugal, Sep. 1989, pp. 555–560.

[15] A. K. El-Safty, "Analysis of jointless bridge decks with partially debonded simple span beams," Ph.D. dissertation, North Carolina State University, Raleigh, NC, USA, 1994.

[16] A. Caner and P. Zia, "Behavior and design of link slabs for jointless bridge decks," *PCI Journal*, vol. 43, no. 3, pp. 68–80, Jun. 1998, https://doi.org/10.15554/pcij.05011998.68.80.

[17] A. N. Pearson, A. C. Birely, M. Yarnold, and S. Hurlebaus, "Evaluation of Link Slab Performance on Texas Highway Bridges," *Transportation Research Record*, Apr. 2024, Art. no. 03611981241242082, https://doi.org/10.1177/03611981241242082.

[18] R. N. Mothe, "Partial continuity in prestressed concrete girder bridges with jointless decks," M.S. thesis, Osmania University, Hyderabad, India, 2006.

[19] "SAP2000 | Structural Analysis and Design." Computers and Structures Inc, 2022.