

Incremental Finite Element Model for Component Interaction Investigation of a Full-Depth Deck Panel System

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*Abstract: Prefabricated Bridge Elements and Systems (PBES) are widely used in accelerated bridge construction (ABC). One such example is the Parkview Bridge located in Kalamazoo, Michigan. The bridge has four spans with AASHTO Type III girders and full-depth deck panels that are post-tensioned in the longitudinal direction after grouting the joints between panels and forming the longitudinal joint with cast-in-place concrete. Structural system behavior is further complicated due to skew and the continuous nature of the post-tensioned deck panels that are connected to the girders using a discrete stud system and grouted haunches. The structural system behavior of bridges constructed using prefabricated bridge elements or systems is very complicated due to component interaction during construction and under service conditions. Advanced finite element (FE) tools and concepts can be utilized to understand component interaction and structural system behavior and to investigate state of stress in components and at connections during construction and under service conditions for verification of design assumptions. This paper presents use of contact simulation and *MODEL CHANGE features in Abaqus to simulate the construction process of the 23-degree skew Parkview Bridge for design verification and assessing durability of the structural system.*

1. Introduction

Prefabricated Bridge Elements and Systems (PBES) are widely used in accelerated bridge construction (ABC). One such example is the Parkview Bridge located in Kalamazoo, Michigan (Figure 1). The twenty three degree (23°) skew Parkview Bridge was designed with four spans and three traffic lanes, with all its major bridge elements including substructure prefabricated off site. The superstructure is composed of 7 prestressed concrete (PC) Type III AASHTO girders and 48, 9-inch thick precast reinforced concrete deck panels that are post-tensioned in the longitudinal direction after grouting the joints between panels and forming the longitudinal joint with cast-in-place concrete (Figure 2). Using full-depth precast deck panels is an innovative technique that brings all the benefits listed under ABC. However, this technique needs to be evaluated and the performance of the bridge needs to be investigated.



Figure 1. Parkview Bridge

The Parkview Bridge superstructure is instrumented using 184 vibrating wire strain gages. All the sensors of this structural health monitoring system are embedded in the full-depth deck panels. Strain and temperature data are collected every 10 minutes, processed, and analyzed. A detailed finite element model of the bridge superstructure was developed and calibrated using sensor data. The calibrated model was used to perform construction process simulation and to develop stress signatures to identify future potential distresses at the deck panel joints. The objective of this paper is to present the use of contact simulation and *MODEL CHANGE features in Abaqus to simulate the construction process of 23-degree skew Parkview Bridge for design verification and assessing durability of the structural system. Additional details of the bridge configuration and health monitoring system are available in (Abudayyeh, 2010).

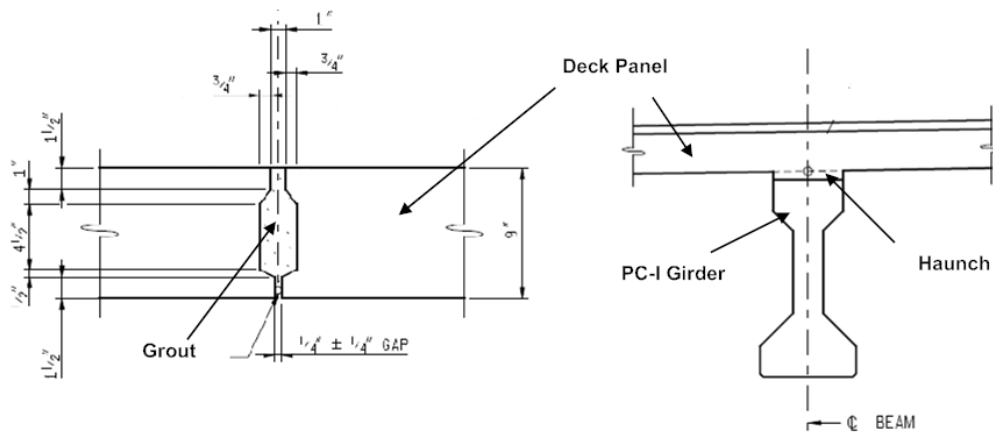


Figure 2. Cross-section view of major components

2. Finite Element Model

The finite element model consisted of full-depth deck panels, PC-I girders, prestressing strands, post-tension tendons, diaphragms, shear keys and haunch. Concrete components were modeled by incompatible Mode 8-node linear brick element (C3D8I). Their disadvantage is the sensitivity to element distortion, which may result in stiffer elements. The element types listed in the following table were used in the model (Table 1).

Table 1. Element types used in FE modeling

Components	Element Types	Definition
Deck Panel	C3D8I	8-node linear brick element (incompatible mode)
Haunch	C3D8I	8-node linear brick element (incompatible mode)
I-beam	C3D8I, C3D6	8-node linear brick element (incompatible mode), 6-node linear triangular prism
Prestress strands Post-tension tendons	T3D2	2-node linear 3-D truss
Grout	C3D8I	8-node linear brick element (incompatible mode)
Intermediate diaphragm	B31	2-node linear beam
End diaphragm	MPC, Beam	Rigid Beam Element

Simply supported PC-I girder models with prestressing strands (Figure 3) were developed representing girder geometries and prestressing strand profiles for each span. Strands were lumped into groups. They were modeled in groups maintaining the strand eccentricity by considering the total cross-section area of strands. Furthermore, details of bridge configuration and modeling can be found in (Abudayyeh et al., 2012)

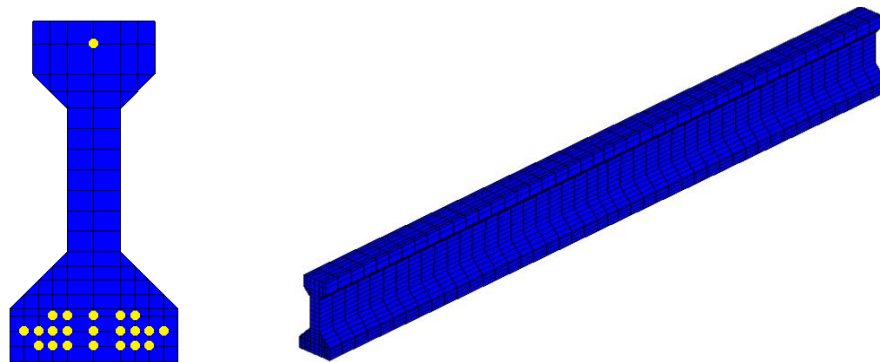


Figure 3. PC-I beam model with prestressing strands

Linear elastic material properties were used in the model because the structure was analyzed under construction and service load conditions where small elastic strains can be assumed. Table 2 shows the material properties used in the model.

Table 2. Material properties

Description		Density (lb/ft ³)	Strength (psi)	Modulus of elasticity (ksi)	Poisson's ratio
Deck Panel		150	8,000	5,000	0.2
Haunch		150	8,000	5,000	0.2
I-beam	at release	150	5,700	4,303	0.2
	at service	150	7,000	4,769	0.2
Prestress strands (0.6" ϕ , 270 ksi low relaxation)		491	270,000	28,500	0.3
Post-tension tendons (0.6" ϕ , 270 ksi low relaxation)		491	270,000	28,500	0.3
Grout			8,000	5,000	
CIP closure		150	6,000	4,415	0.2
Intermediate diaphragm		491	60,000	29,000	0.3

3. Contact Surface Modeling

The bridge has a 23 degree skew. Girders are placed parallel to the bridge longitudinal axis, and their ends are kept perpendicular to the longitudinal axis. Deck panels are placed parallel to pier or abutment axes (i.e., parallel to the skew). Because of these reasons, it was necessary to develop two different mesh configurations for the girders and deck panels. Furthermore, a refined mesh configuration was used for deck panels to maintain their maximum aspect ratio of less than five. Five is considered to be the critical aspect ratio for stress analysis. These dissimilar mesh configurations require providing contact surfaces to establish girder and deck panel interaction. Design details show that bridge superstructure is restrained for vertical, lateral, and transverse directions at pier 2 (Figure 4). Expansion bearings are used at pier 1 and 3 which do not prevent uplift of girders. Hence, model required releasing upward and longitudinal translations at pier 1 and 3 while restraining the downward movement of girder ends. This specific boundary condition required using contact interaction between the pier and girders.

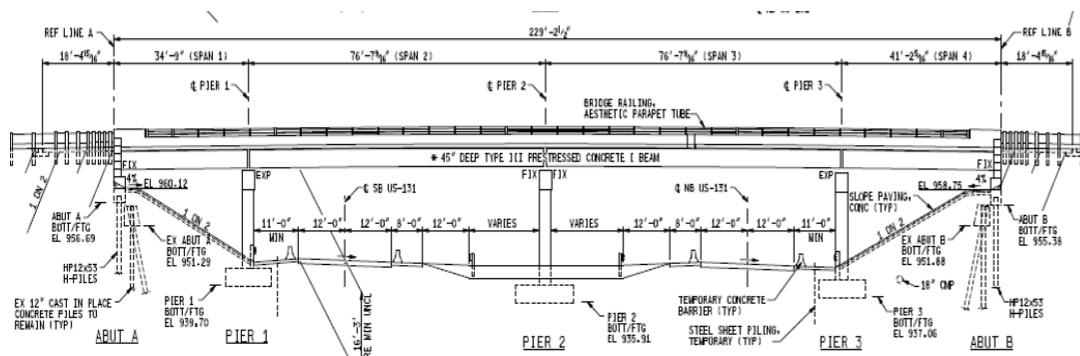


Figure 4. General plan of structure

Abaqus/Standard allows three different types of contact analysis: general contacts, contact elements and contact pairs. Contact elements are applicable only if two bodies cannot be modeled by using general contact and contact pairs such as gap contact elements, tube-to-tube contact

elements, slide line contact elements and rigid surface contact elements (Simulia, 2010). Both contact pairs and general contact have similar underlying algorithms and use surfaces to define interaction. General contact provides easiness and flexibility when defining contact definition due to its all-inclusive self-contact approach. On the other hand, contact pairs require definition of surfaces which may interact with each other during contact simulation. Furthermore, master and slave roles must be defined carefully by a user in contact pairs whereas general contact perceives the definition automatically. Although contact pairs require user effort and have negative impact on analysis time, usage is more efficient and often result more robust analyses (Simulia, 2010). Hence, interaction between two dissimilar meshes was defined by using contact pairs.

3.1 Interaction between haunch and deck panels

Master and slave surfaces were generated between the beam and haunch and haunch and deck panels (Figure 5). Then surface behavior was defined by using the no separation relationship which does not allow surface separation after they are in contact. Hard contact relationship that minimizes the penetration of the surfaces into each other is used to define pressure-overclosure relationship. Tied contact for contact pair was used with no separation interaction behavior. Tied surfaces require adjustment which was decided as 0.1 because tied surfaces should be defined precisely in contact; however, the maximum adjustment was monitored as $2.22\text{E-}16$.

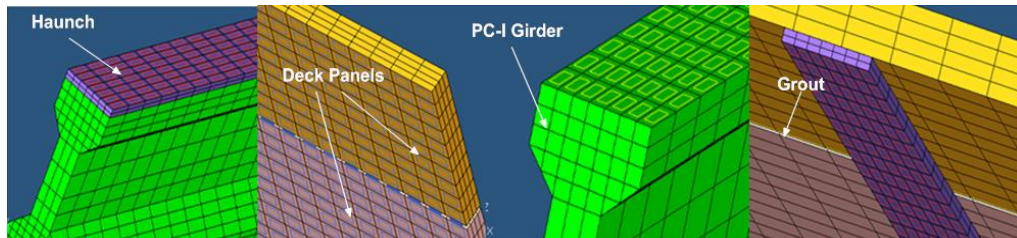


Figure 5. Contact surfaces

3.2 Interaction between pier and girder ends

As discussed above, the girder ends over pier 1 and 3 are not constrained to prevent upward and longitudinal movements. Hence, master and slave surfaces were generated between pier top and girder end bottom surfaces (Figure 6). Hard contact relationship was assigned to pressure-overclosure with linear penalty method for surface behavior. Hence, surfaces will not be able to penetrate each other whereas separation is allowed when the contact pressure between them is tensile. Contact pairs also allow temporary activation and deactivation of surfaces between steps when surfaces are not tied. This feature was very helpful when construction process simulation was performed, as discussed in Section 4.

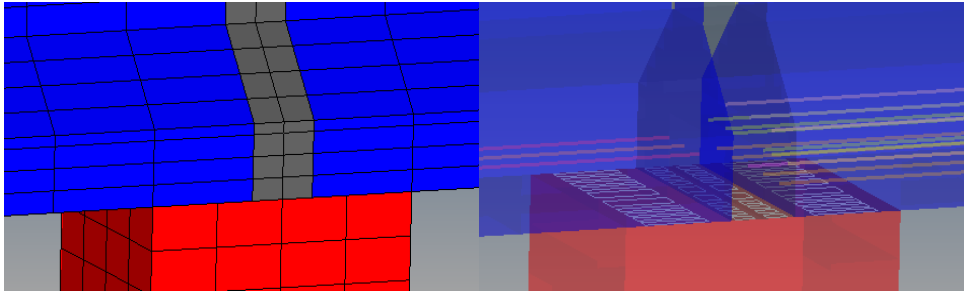


Figure 6. Contact surface between pier and girder ends

4. Construction Process Modeling and Simulation

The structural system behavior of bridges constructed using prefabricated full-depth deck panels is very complicated due to component interaction during construction and under service conditions. Therefore, a detailed finite element model was developed and calibrated using sensor data collected from the structural health monitoring system. Construction process was simulated to understand the prefabricated component interaction and to assess the durability performance of the bridge.

Abaqus/Standard version 6.11 allows removing and adding elements by using ***MODEL CHANGE, REMOVE (ADD)=STRAIN FREE** during analysis. Strain-free option was used because the connections were established using fresh grout material which was not capable of transferring any loads until hardened. Further, in the model, the new elements that represent the strain free components or materials of the bridge were added to already deformed configurations requiring use of strain free option. When elements are added in strain-free state Abaqus/Standard investigates the shape of the element to redefine their orientations and to calculate their masses.

Dell OptiPlex Tower with 4 CPU Intel(R) Xeon(R) CPU 5160 @3.00GHz and Red Hat Enterprise Linux WS release 4 (Nahant Update 6) operating system was used. 101,561,995 Bytes model was used for analysis and total time needed to finish analysis was 5003.3 seconds.

4.1 Component Interaction

The step-by-step process of the Parkview Bridge superstructure construction is presented below.

1. Erection of PC-I beams,
2. Installation of shim packs on the girders,
3. Installing full-depth deck panels over the shim packs (note that the shim packs only restrained the vertical downward movement of the panels),
4. Grouting transverse deck panel joints,
5. Completion of cast-in-place closure joint,
6. Installation and stressing of post-tensioning tendons (this action was performed once the joint material attained the specified strength), and
7. Grouting haunches and shear pockets.

Use of ***MODEL CHANGE** requires developing the complete model. This was accomplished and the model was calibrated using sensor data. Further information on model calibration can be found in (Abudayyeh et al., 2012). Construction process simulation of the bridge superstructure required removing all the elements except girders, full-depth deck panels, grout, closure, prestressing strands, and the post-tensioning strands. Self-weight of the haunch and deck panel was calculated and applied on the interior and exterior girders. Construction process simulation was challenging because the deck panels were temporarily supported over the girders using shim packs while post-tensioning was applied to the panels. However, there was no transfer of post-tension load to the girders as the deck panel assembly was free to translate in any direction, except vertically downward. Further, during the simulation process, prestressing of girders and post-tensioning of the deck panels were simulated at the same time. Hence, deck panels were supported by defining temporary boundary conditions that are independent of the rest of the model. Once the deck panels were post-tensioned and the girders were pretensioned, the temporary boundary conditions and the applied load on the girder were removed, and the elements representing haunches were added to the model. Consequently, the complete bridge superstructure model was developed through the simulation. A few major steps of the construction process are shown in **Error! Reference source not found.**

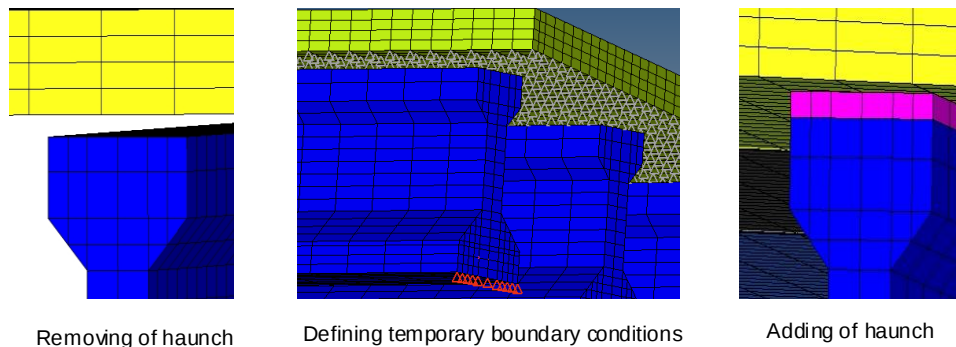


Figure 7. Construction process simulation

Same model with and without ***MODEL CHANGE** was analyzed under the same loads and boundary conditions to examine end stresses after construction. Implementation of construction process simulation with ***MODEL CHANGE** shows that all the deck panel joints were in compression and the values were at around -400 psi, as expected at the design (Figure 8**Error! Reference source not found.**); whereas simulation without ***MODEL CHANGE** shows significant variations of deck panel stresses.

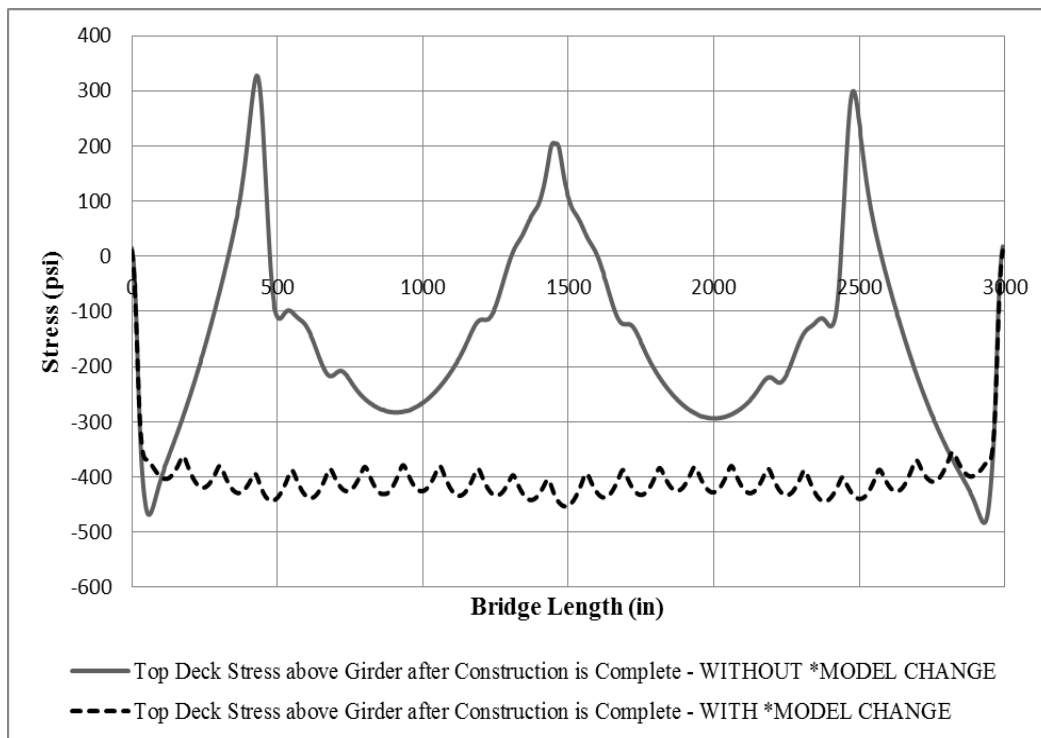


Figure 8. End stresses after construction

4.2 Post-tensioning sequence

The full-depth deck panel assembly was post-tensioned using strands that were placed in 14 ducts. Initial post-tension force applied at each location was 182.8 kips. The spacing between post-tension ducts is shown in Figure 9. The post-tension tendon size, tendon length, stressing force, stressing end, and stressing sequence are shown in **Error! Reference source not found.** Table 3.

In the bridge, transverse female-to-female type full-depth deck joints were filled with non-shrink grout. As discussed above, at the end of construction, all the transverse joints are under compression. However, the stress development at the joints during the post-tensioning process should be investigated because not only eccentricity but also skew and post-tension losses due to subsequent stretching may lead to the development of tensile stresses. The simulation required defining surfaces at grout and deck panel interfaces to simulate contact interaction and to calculate principal stresses. After all the tendons were deactivated by removing elements, each tendon was activated following the sequence presented in **Error! Reference source not found.** Table 3.

Simulation results showed that the maximum tensile stress developed at the transverse joint is about 22 psi which is much lower than the non-shrink grout direct tensile failure strength of 75 psi documented in literature (Gulyas et al., 1995). Further, at the end of construction, all the joints were under compression. Therefore, transverse joints are performing as expected at the design stage.

Table 3. Post-tension details

PT Designation	Tendon Size	Tendon Length	Stressing Force (kips)	Stressing End	Stressing Sequence
L1	4×0.6"	245'-6 1/4"	182.8	ABUT A	6
L2	4×0.6"	245'-6 1/4"	182.8	ABUT B	14
L3	4×0.6"	245'-6 1/4"	182.8	ABUT A	1
L4	4×0.6"	245'-6 1/4"	182.8	ABUT B	8
L5	4×0.6"	245'-6 1/4"	182.8	ABUT A	5
L6	4×0.6"	245'-6 1/4"	182.8	ABUT B	11
L7	4×0.6"	245'-6 1/4"	182.8	ABUT A	3
L8	4×0.6"	245'-6 1/4"	182.8	ABUT B	10
L9	4×0.6"	245'-6 1/4"	182.8	ABUT B	12
L10	4×0.6"	245'-6 1/4"	182.8	ABUT A	4
L11	4×0.6"	245'-6 1/4"	182.8	ABUT B	9
L12	4×0.6"	245'-6 1/4"	182.8	ABUT A	2
L13	4×0.6"	245'-6 1/4"	182.8	ABUT B	13
L14	4×0.6"	245'-6 1/4"	182.8	ABUT A	7

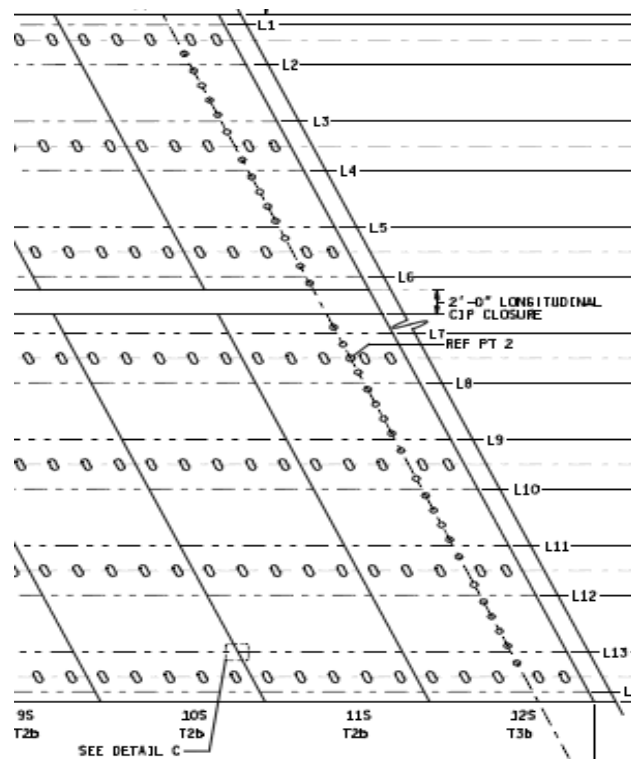


Figure 9. Post-tensioning layout

5. Conclusions and Summary

The twenty three degree (23^0) skew Parkview Bridge has taken advantage of the accelerated bridge construction (ABC) technique. The bridge superstructure consists of full-depth precast deck panels. The connection between individual panels is established through grouted transverse joints, cast-in-place longitudinal concrete closure pour, and longitudinal post-tensioning. The connection between deck panels and girders is established through grouted haunch and grouted shear pockets with studs. The structural system behavior of bridges constructed using prefabricated full-depth deck panels is complicated due to component interaction during construction and under service conditions. A detailed finite element model was developed and calibrated using sensor data collected from the health monitoring system implemented in the bridge. Advanced analysis options available in Abaqus such as contact interaction and ***MODEL CHANGE** allowed construction process simulation of the bridge seamlessly. The unique challenges faced during modeling and simulation were diligently handled using Abaqus capabilities. The analysis results shows that the bridge is performing as expected at the design stage. However, the analysis did not include construction quality parameters; hence, further studies are needed to incorporate these parameters to evaluate structural performance in terms of durability. .

6. References

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