
Identification of prestress loss in PC bridges using static displacement responses under a moving vehicle

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ABSTRACT

Prestress loss in concrete bridges is a critical phenomenon that can compromise structural performance and, if undetected, lead to severe safety risks. Identifying such changes is challenging due to the internal nature of prestressing. This study presents a data-driven approach for identifying global prestress loss in a prestressed concrete (PC) bridge subjected to a moving vehicle. A finite element model (FEM) of a PC bridge was used to simulate vehicle-induced responses under various prestress states. Displacement data were analysed through comparative evaluation of vertical nodal displacements across bridge girders under moving load conditions. Variations in the transverse displacement distribution were then assessed to identify the presence, location, and severity of prestress loss.

1 INTRODUCTION

Prestress loss in PC bridges is a critical structural issue that can compromise serviceability and safety. Unlike conventional deterioration mechanisms, prestress loss occurs internally within the bridge's tendons and is often difficult to detect using routine inspections. The inability to directly assess the condition of prestressing tendons has historically contributed to several notable structural failures (Ding and Cao, 2024), emphasizing the need for effective detection and monitoring strategies.

Undetected prestress loss in PC bridges is especially dangerous in more seismically active regions, such as New Zealand. Previous studies have shown that prestress loss can increase seismic vulnerability (Yuen et al., 2021), having a significant impact on seismic response of a structure (Mo and Hwang, 1996). For this reason, even more attention should be paid to prestress loss detection in such regions.

Within the field of structural health monitoring (SHM), various approaches have been developed to identify prestress loss, broadly classified into methods based on static and dynamic bridge responses (Zhang et al., 2025). Static methods primarily rely on measuring displacements or strains under applied loads (Nguyen et al., 2016). Among these, vertical displacement is particularly informative, as it directly reflects changes in structural stiffness, which are indicative of prestress loss or other forms of damage (Yoshida et al., 2024). Numerous studies have demonstrated the potential of static displacement-based methods for detecting damage in PC bridges, employing techniques such as optical-fiber-sensor-based monitoring (Xuan et al., 2009), influence line analysis (Zhang et al., 2023) and deflection comparison (Zhou et al., 2021).

However, much of the existing research has focused on detecting prestress loss by comparing measured responses to baseline conditions at individual points, without fully considering the overall behaviour and interactions between different structural elements.

This study addresses these limitations by examining the transverse distribution of vertical displacements across multiple girders in a PC bridge under a moving vehicle load. Using a FEM model of a representative bridge, different prestress loss scenarios are simulated, and the resulting displacement responses are analysed to identify the presence and location of prestress loss.

2 CASE STUDY

2.1 Bridge

As the case study, a PC bridge (Wenxi Bridge) was selected. The bridge has five T-shaped prestressed girders supporting a 157 mm thick concrete deck slab (Figure 1). Each girder has a cross-section height of 200 mm and is prestressed with three individual tendons. The overall span of the bridge is 30 m in the longitudinal direction and approximately 9 m in the transverse direction between the centrelines of outer girders. Accounting for edge overhangs, the total width of the deck slab is 12.5 m. A detailed FEM model of the Wenxi Bridge was constructed in Abaqus to simulate static responses under moving vehicular loads. The model has been previously validated against static proof load test results (Sun, 2021).

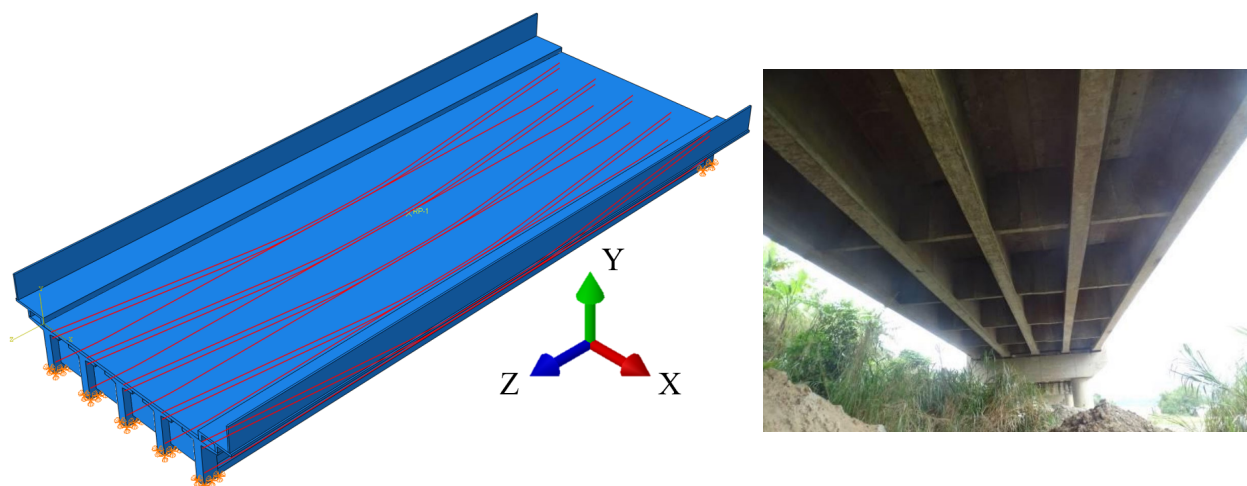


Figure 1: Wenxi bridge (numerical model and real bridge)

2.2 Moving vehicle

For the moving load, a 4-axle vehicle based on the Fatigue Load Model 3 configuration from Eurocode (EN 1991-2, 2003) was used. The vehicle consists of four axles, each carrying a load of 120 kN. The exact axle spacing is shown in Figure 2. This vehicle was selected to represent a relatively heavy load, allowing the simulation to capture a clear structural response for the study. The vehicle was placed on one side of the

bridge, with the centre of the outer tire 0.5 m from the deck edge, to create asymmetric behaviour and induce measurable reactions in the structure.

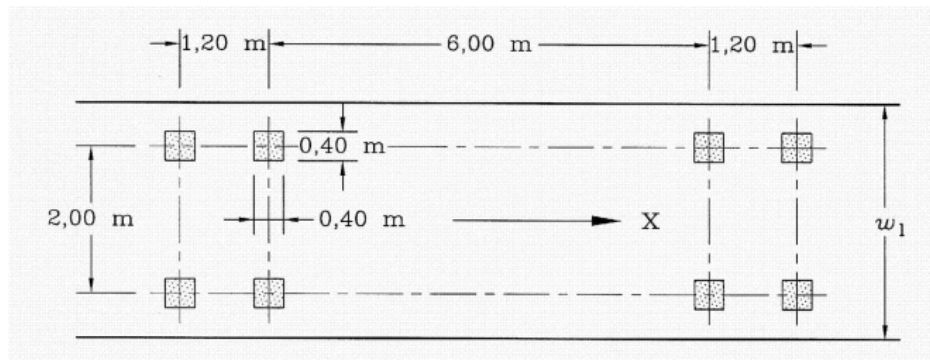


Figure 2: 4-axle vehicle load

Given that the analysis uses a static FEM model, the vehicle speed does not significantly influence the results. A speed of 50 km/h was chosen primarily to ensure a sufficient length of the simulation for displacement extraction along the bridge span. The timings of the axles entering and exiting the bridge are as follows: the first axle enters at 0 s, followed by the second, third, and fourth axles at 0.0864 s, 0.5184 s, and 0.6048 s, respectively. At this speed, the vehicle takes 2.16 s to cross the bridge, leaving at 2.16 s, 2.25 s, 2.68 s, and 2.77 s for each axle. Each prestress loss scenario was simulated using a 3-second static, general step, corresponding to the full traversal of the vehicle along the 30 m bridge span, to evaluate the resulting displacement response of the structure.

2.3 Prestress loss scenarios

All tendons were initially modelled with a prestress force corresponding to 1.395×10^9 Pa, applied to the concrete via an initial temperature load to simulate prestress introduction, as commonly used in literature (Ren et al., 2015). To investigate the effect of prestress loss, the upper tendon of each girder was reduced in prestress in five separate cases, with one case per girder. In these cases, D1 corresponds to damage on the same side as the moving vehicle, while D5 represents damage on the opposite side. For each girder, three levels of prestress loss were considered: 1.0×10^9 Pa, 0.5×10^9 Pa, and complete loss (0 Pa), corresponding to 28 %, 64 % and 100 % prestress loss. This resulted in a total of 15 prestress loss scenarios for analysis. Each scenario was simulated using a 3-second static, general step, corresponding to the full traversal of the vehicle along the 30 m bridge span, to evaluate the resulting displacement response of the structure.

3 RESULTS AND DISCUSSIONS

For the results analysis, five nodes were selected at the midspan of the bridge, one per girder. These nodes are denoted as Nodes 1–5, ordered from the side opposite the vehicle location to the side directly underneath the moving vehicle. Figure 3 presents representative results for one of the investigated nodes (Node 2). These show quasi-static component of the moving vehicle load, as only static simulation was performed. In real-world measurements, a quasi-static displacement component extraction would be necessary, such as by lowpass filter (Peng et al., 2024). The displacement response of the bridge is shown in all three directions (X – transverse, Y – vertical, Z – longitudinal) under the moving vehicle load, with the dominant response occurring in the vertical (Y) direction, as expected. While the vertical displacement increased consistently in all prestress loss scenarios, changes in the transverse and longitudinal displacements exhibited more varied behaviour. In the transverse direction, positive displacements were observed in damage cases D5 and D4, corresponding to girders located on the side opposite the vehicle. In the longitudinal direction, positive

displacement was primarily observed for case D1, where damage was located beneath the vehicle path. This behaviour is consistent with the asymmetric vehicle position and the resulting load distribution across the bridge width. Figure 3(d) illustrates the spatial trajectory of Node 2 under the moving vehicle, highlighting the combined displacement response during vehicle crossing.

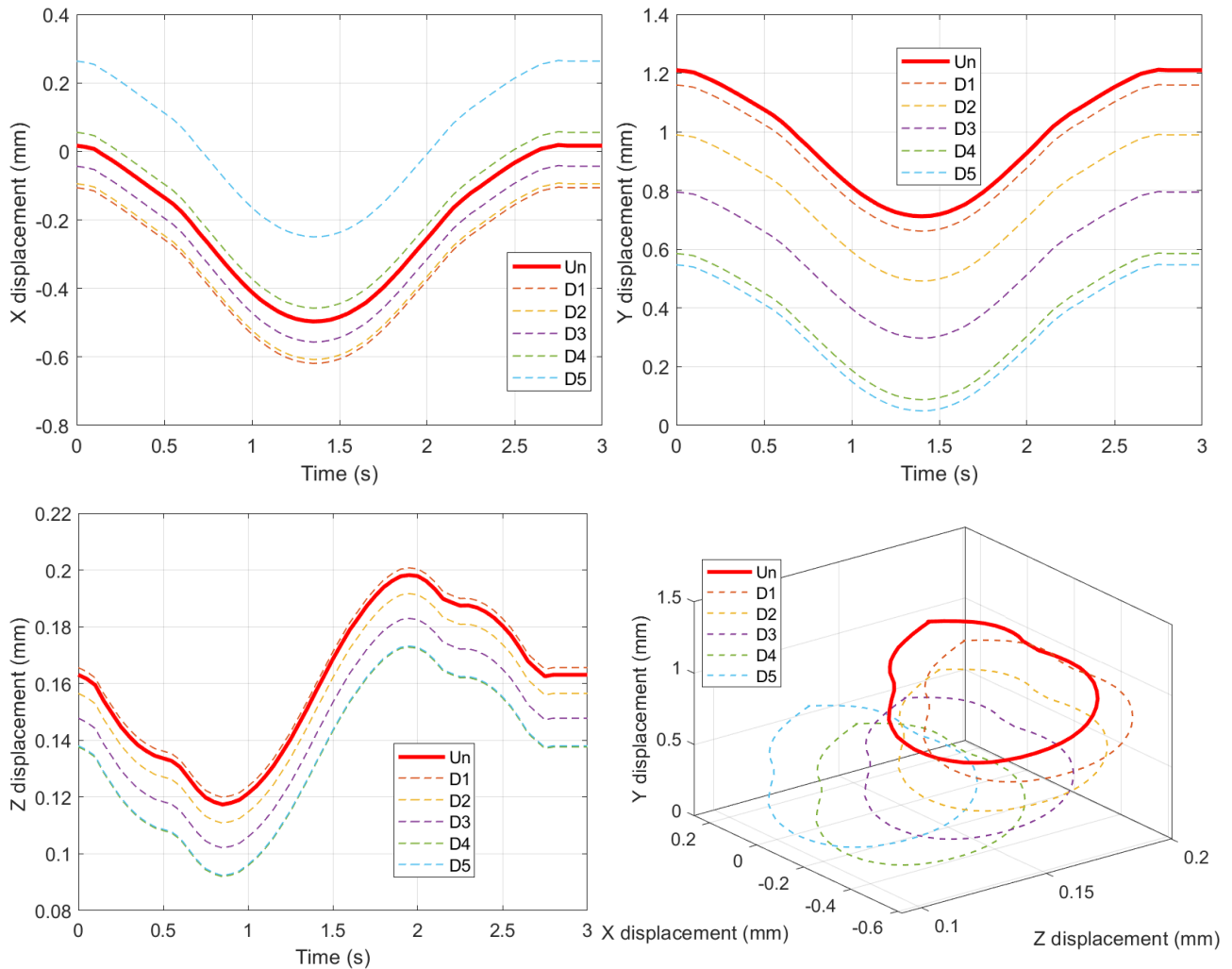


Figure 3: Displacement at Node 2

Based on these observations, the vertical displacement (Y direction) was examined in more detail at the time corresponding to the maximum response, occurring at 1.4 s. As shown in Figure 4, the largest vertical displacement in all cases occurs at Node 5, which is directly beneath the vehicle, as expected. The vertical displacements across the five girders form a transverse displacement profile that resembles a transverse influence line. The slope of this profile varies depending on the location of the prestress loss. Damage located beneath the vehicle (case D1) produces the steepest transverse slope, while damage on the opposite side of the bridge (case D5) results in the smallest slope. In more severe prestress loss cases (0.5×10^9 Pa or lower), the displacement at Node 1 becomes smaller than that at Node 2, further highlighting the effect of damage location on the transverse displacement distribution.

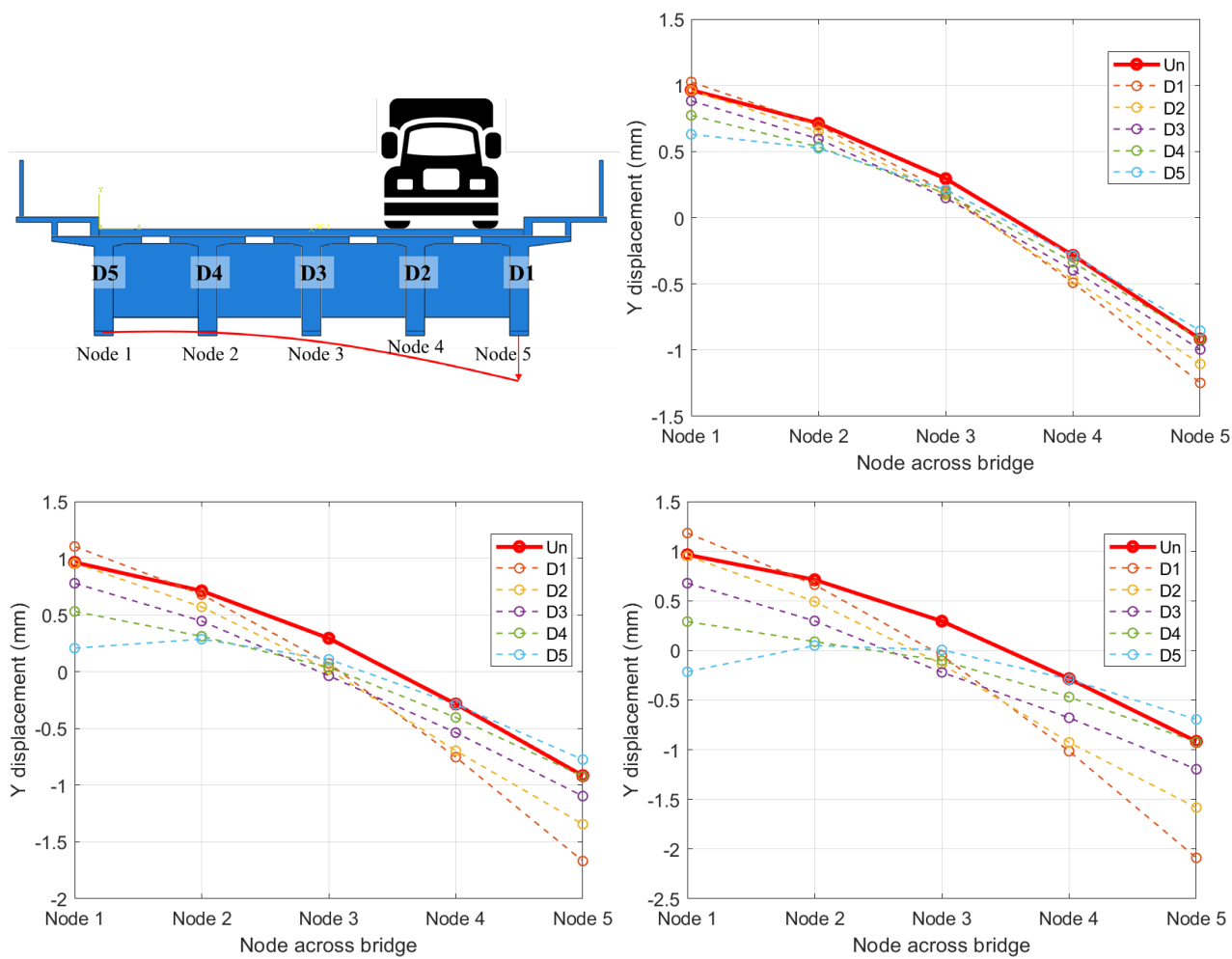
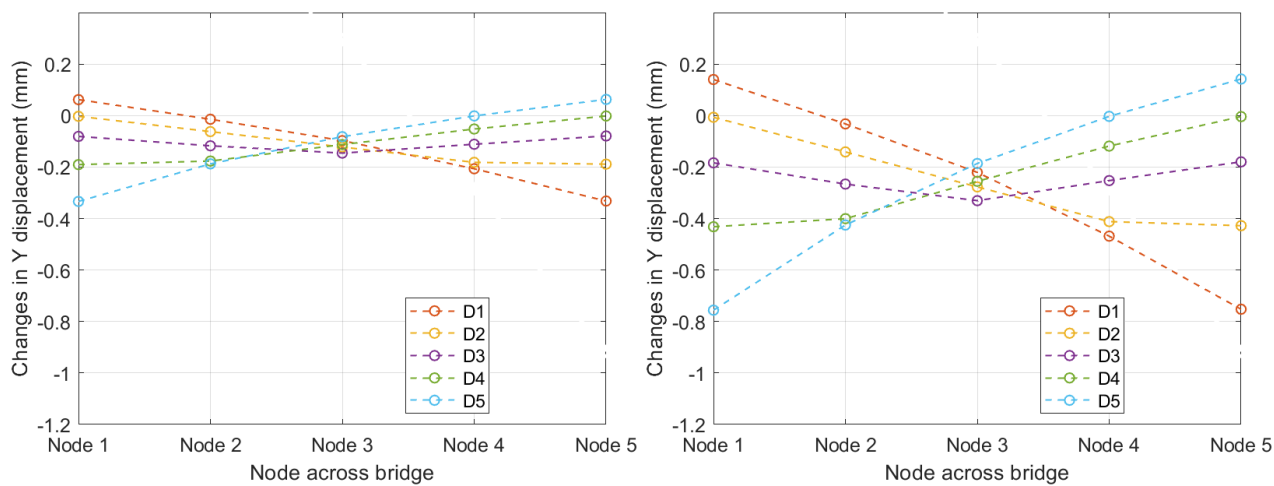


Figure 4: Node displacement across the bridge

Further insight is obtained by comparing the damaged cases with the undamaged baseline response (Figure 5). The difference between damaged and undamaged displacements reveals a distinct change in slope at the location of prestress loss, resulting in a discontinuity in the transverse displacement gradient. This behaviour is evident even in less severe prestress loss scenarios, such as the 1.0×10^9 Pa case (Figure 5(d)), indicating that localized prestress reduction can be identified through changes in the transverse displacement pattern.



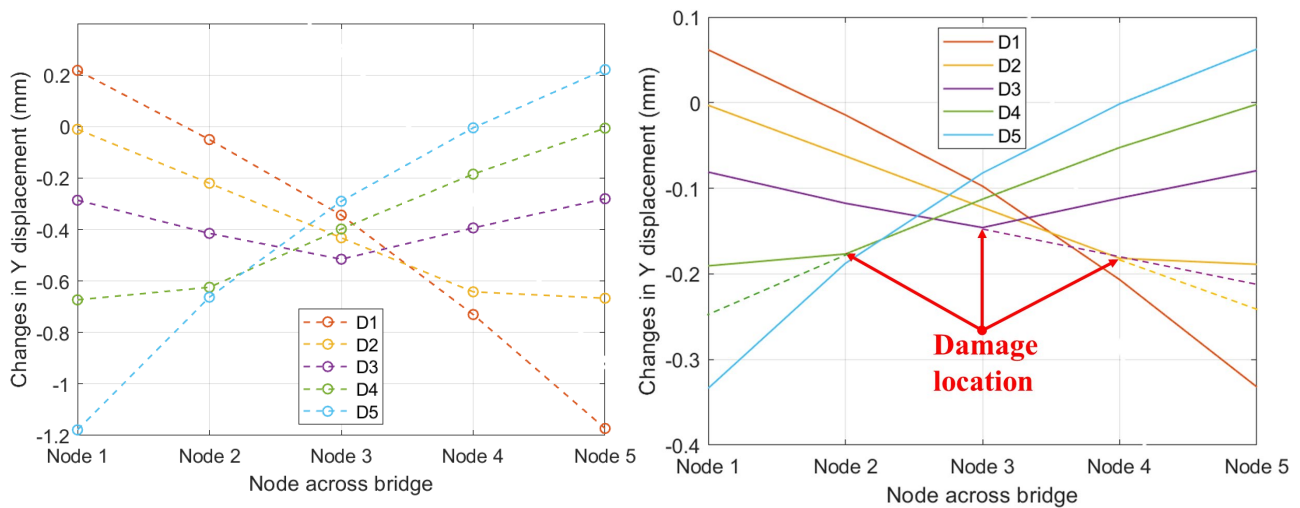


Figure 5: Changes in vertical node displacement across the bridge

4 CONCLUSION

A total of 15 damage cases representing different locations and severities of prestress loss were investigated. Displacement responses at multiple nodes across the bridge width were analysed and compared against the undamaged baseline condition. The results demonstrated that variations in vertical displacement patterns across the girders can provide clear indications of the presence and location of prestress loss. In particular, analysing the relative behaviour between adjacent nodes proved essential for detecting structural changes, highlighting the importance of considering the interaction and correlation of displacement responses across the bridge rather than evaluating individual measurement points in isolation.

5 LIMITATIONS AND FUTURE WORK

This study has several limitations that should be considered:

- The results are based on an idealised FEM model; real bridge measurements would be affected by sensor noise, environmental influences, and measurement uncertainty.
- In real structures, prestress loss may be partially compensated by structural redistribution, cracking behaviour, or time-dependent material effects, potentially masking stiffness changes.
- Prestress loss detection is unlikely to be reliably achieved solely using transverse vertical displacement variations across girders.

Future work will focus on:

- Incorporating measurement noise and uncertainty into the analysis.
- Investigating identification under realistic traffic loading scenarios.
- Combining displacement responses with additional monitoring parameters (e.g., strain, acceleration, or modal properties) within a multi-parameter damage detection framework.

6 ACKNOWLEDGEMENT

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