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ULTRA-HIGH-PERFORMANCE-CONCRETE FOR IMPROVED COLLISION RESISTANCE OF PREFABRICATED PIERS

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Abstract

As accelerated bridge construction continues to gain momentum, prefabricated substructure systems are increasingly being implemented in bridge projects. To connect adjoining prefabricated components, socket connections are advantageous due to their simple construction procedures and relatively low tolerance demands. In particular, challenges exist for precast concrete columns connected to pile-shaft foundations through socket connections, because these systems rely on thin-walled pile shafts for load transfer to the ground, making them inherently vulnerable to the concentrated shear demands induced by vehicular collisions. This study examines the effectiveness of ultra-high-performance concrete (UHPC) pile shafts in improving the shear resistance and deformation capacity of socket-connected precast bridge substructures. Two geometrically identical specimens were fabricated, differing only in pile shaft material—normal concrete (NC) and UHPC. Quasi-static lateral loading was applied near the ground level to reproduce the critical demand conditions associated with vehicle collisions. Notable differences in structural response and failure characteristics were observed. The NC pile shaft specimen developed significant shaft prying damage accompanied by column flexural damage. In contrast, the UHPC pile shaft specimen exhibited damage largely confined to the column, with the pile shaft remaining essentially intact. Quantitatively, the UHPC configuration achieved a 17% increase in lateral strength and more than a 60% enhancement in deformation capacity relative to its NC counterpart. The results suggest that incorporating UHPC in pile shafts can promote a more desirable failure mechanism, offering a possible strategy for improving the collision resilience of precast bridge substructures.

Keywords: *precast concrete columns; socket connections; pile shafts; ultra-high-performance concrete; shear performance*

1. Introduction

Accelerated bridge construction (ABC) has gained increasing attention in recent decades as a strategy to reduce on-site construction time, minimize traffic disruption, and improve construction quality (Akhnoukh 2020). A key component of ABC is the use of prefabricated bridge elements and systems, in which structural components are manufactured off-site and rapidly assembled in the field (Jiang et al. 2024). Within prefabricated bridge substructures, reliable and efficient connection systems are essential to ensure structural integrity and facilitate rapid construction. Among various connection approaches, socket connections have attracted interest because of their simple construction procedures, relatively low tolerance requirements, and ease of implementation in the field (Cheng and Sritharan 2019).

Despite these advantages, socket connections have been used less frequently in precast column-to-pile shaft systems compared with other precast bridge substructure connections. This is largely because that thin-walled cast-in-drilled-hole pile shafts, although attractive where a smaller foundation footprint is required, present distinct structural vulnerabilities. Under lateral loading, their load transfer mechanism can induce significant prying action in the pile shaft, which may lead to splitting failure of the pile shaft (He et al. 2024). Failure of the pile foundation is generally considered the most unfavorable failure mode because it compromises the stability of the entire structural system and is difficult to repair. To mitigate this risk and ensure adequate confinement of the column, conventional design approaches typically rely on increasing the pile shaft diameter, raising the transverse reinforcement ratio, or enlarging the socket embedment depth. However, these measures often increase construction complexity and cost, thereby reducing the practical advantages of socket connections.

Existing studies on precast column-to-pile shaft systems with socket connections have primarily focused on their seismic performance (Zou et al. 2023; Yang et al. 2024; He et al. 2026). While valuable insights have been gained regarding their cyclic behavior and ductility under earthquake loading, their structural safety under impact loading remains largely unexplored. This issue is becoming increasingly important in modern transportation infrastructure. With climate change contributing to accelerated bridge deterioration (Xu and Yang 2025) and more frequent extreme events, and with the continued growth in vessel sizes and vehicle ownership, accidental collisions involving ships and vehicles occur periodically and pose a serious threat to bridge safety. In this context, concerns remain regarding the collision resistance of socket-connected pile-column bridge substructures, which has hindered their broader adoption in practice.

Therefore, developing an efficient and reliable connection configuration is a critical prerequisite for promoting the application of socket-connected precast bridge substructures. Ultra-high-performance concrete (UHPC) has emerged as a promising material in bridge engineering due to its exceptionally high compressive strength, enhanced tensile resistance, and superior durability. The objective of this study is to investigate the effectiveness of UHPC in addressing the vulnerability of precast concrete columns connected to thin-walled pile shaft foundations, which struggle to resist shear forces induced by vehicular collisions. Through experimental testing of two geometrically identical specimens—one with a normal concrete pile shaft and the other with a UHPC pile shaft—this study evaluates the influence of UHPC on the structural response, failure mechanisms, and deformation capacity of socket-connected precast bridge substructures under lateral loading representative of vehicle collision demands.

2. Experimental Design

2.1 Specimen Design

Two 1/3-scale specimens were designed and fabricated for testing, as illustrated in Fig. 1. The two specimens were identical in geometry and reinforcement details, except for the material used in the pile shaft. Specimen #1 employed a normal concrete (NC) pile shaft, whereas Specimen #2 used an ultra-high-performance concrete (UHPC) pile shaft.

The precast column had a circular cross-section with a diameter of 500 mm and a total height of 2,000 mm, of which 500 mm was embedded into the pile shaft to form the socket connection. The column was reinforced with twelve 15M longitudinal bars, corresponding to a longitudinal reinforcement ratio of 1.22%.

Transverse reinforcement consisted of 10M hoops spaced at 60 mm center-to-center, resulting in a volumetric reinforcement ratio of 1.52%.

The pile shaft had an outer diameter of 750 mm. Longitudinal reinforcement was provided by thirty-four 15M bars, while 10M transverse reinforcement was arranged at a spacing of 80 mm center-to-center. The corresponding longitudinal and transverse reinforcement ratios of the pile shaft were 1.54% and 0.76%, respectively.

Material properties were determined through standard compression tests. The measured compressive strengths of normal concrete used for the precast column, pile shaft, and concrete base were 38 MPa, 47.3 MPa, and 43.1 MPa, respectively. For Specimen #2, the UHPC used in the pile shaft had a measured compressive strength of 142 MPa. All reinforcing steel used in the specimens had a nominal yield strength of 400 MPa.

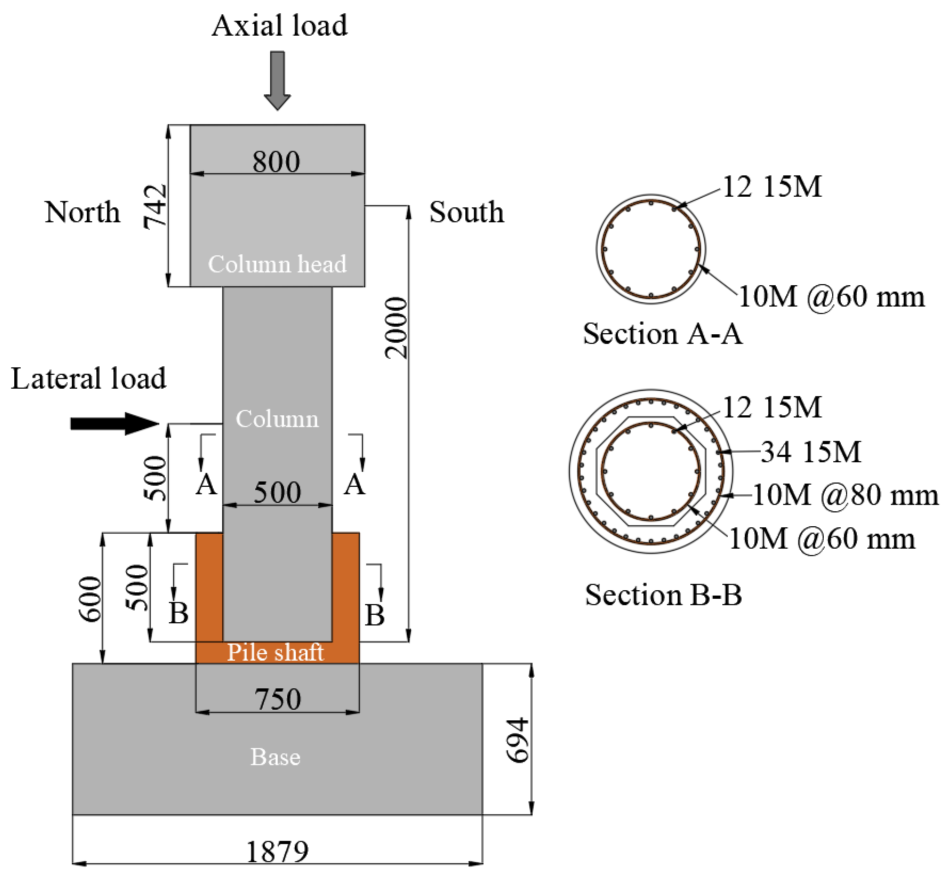

Fig. 1 Specimen design and reinforcement details (Unit: mm)

2.2 Test Setup and Loading Scheme

The experimental setup is illustrated in Fig. 2. Each specimen was subjected to a constant axial load combined with a monotonically increasing lateral load, applied through vertical and horizontal actuators, respectively.

The axial load was applied using two hydraulic jacks with a capacity of 50 tons each, which were connected to a steel beam positioned above the column head to simulate the weight of the bridge superstructure. The total axial load applied to each specimen was 170 kN, corresponding to an axial load ratio of 2.5%. The axial load was applied under force control and maintained constant throughout the entire test.

Lateral loading was applied using a horizontal hydraulic actuator with a capacity of 1,000 kN. The actuator was positioned near the base of the column (500 mm above the interface between the column and pile shaft) to reproduce the critical loading conditions associated with vehicle collisions (Xu et al. 2025). To ensure accurate load transfer to the curved column surface, the swivel head of the actuator was removed, and the load cell was connected to a specially designed loading apparatus. The height of the loading apparatus was set to 170 mm, based on analyses of impact force distributions obtained from extensive numerical simulations of heavy vehicle–bridge collision scenarios.

Prior to lateral loading, the prescribed axial load was applied using the two vertical actuators operating in force-control mode. After the target axial load was reached and stabilized, the lateral load was applied under displacement-control mode at a rate of 0.5 mm/min. This loading rate ensured that the shear strain rate in the column remained well below the typical strain rate range associated with quasi-static testing.

The lateral loading continued until either a 20% reduction in lateral load capacity was observed or a potential risk of instability in the test setup was identified. At that point, the lateral load was gradually reduced to zero in order to examine the residual deformation and recovery behavior of the specimens after experiencing significant damage.

A comprehensive instrumentation system was employed to monitor the structural response during testing. Linear variable differential transformers (LVDTs) were used to measure relative vertical displacements, string potentiometers were installed to record lateral deflections, and strain gauges were attached to selected reinforcement bars to capture the strain response of the steel reinforcement.

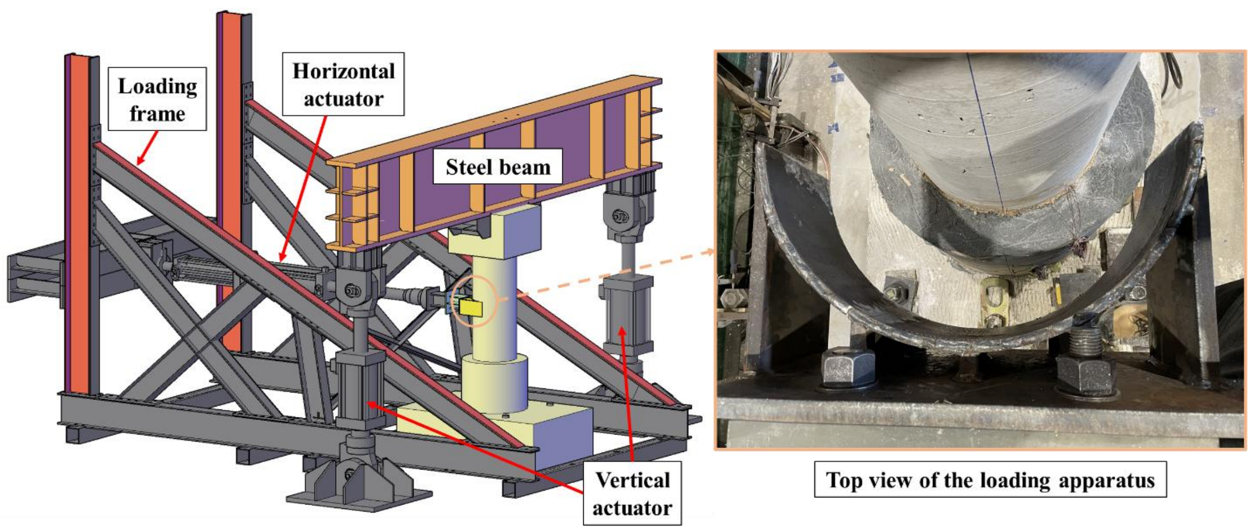

Fig. 2 Test setup

3. Experimental Results

3.1 Damage Mode

The final damage states of the two specimens are shown in Fig. 3. Although both specimens were subjected to the same loading protocol, distinct failure patterns were observed due to the difference in pile shaft material.

For Specimen #1, which employed a normal concrete (NC) pile shaft, the final damage state indicates a combination of failure mechanisms involving both the pile shaft and the column. The pile shaft experienced pronounced shaft prying damage, manifested by extensive cracking and concrete spalling in the socket region, exposing the shaft reinforcement at multiple locations. In addition to the shaft damage, flexural damage also developed at the base of the column.

In contrast, the final damage state of Specimen #2, which incorporated a UHPC pile shaft, exhibited a markedly different response. As shown in Fig. 3, the UHPC shaft remained largely intact throughout the test, with only minor surface cracking observed. No significant spalling or splitting damage occurred in the socket region, indicating that the UHPC shaft effectively resisted the prying forces induced by lateral loading. Instead, the majority of the structural damage was concentrated in the column region, where severe flexural cracking developed on the tension side, accompanied by localized concrete crushing near the base of the column.

This clear shift in failure location demonstrates that the use of UHPC in the pile shaft successfully prevented damage in the socket region and redirected the failure mechanism toward column flexural behavior, which is generally considered a more desirable and ductile failure mode. The observed damage patterns highlight the ability of UHPC to enhance the robustness of the pile shaft and improve the overall structural resilience of socket-connected precast bridge substructures.

(a) (b)

Fig. 3 Final damage state: (a) specimen #1 and (b) specimen #2

3.2 Force-Displacement Relationships

The lateral force–displacement responses of the two specimens are compared in Fig. 4. Both specimens exhibited similar initial stiffness during the early loading stage, indicating that the difference in pile shaft material had little influence on the elastic response of the system. However, clear differences emerged after the specimens approached their peak strength.

For Specimen #1, the lateral force increased rapidly with displacement and reached a maximum value of 602 kN at a displacement of 18 mm. Beyond this point, the load capacity degraded rapidly. The lateral force dropped to approximately 55% of the peak strength at a displacement of 60 mm, indicating a relatively brittle post-peak response. The onset of strength degradation corresponded approximately to the yielding of the transverse reinforcement in the pile shaft, suggesting that the deterioration of the socket region governed the structural response.

In contrast, Specimen #2 exhibited both higher strength and significantly improved deformation capacity. The specimen reached a peak lateral force of 703 kN at a displacement of 34 mm, representing a 17% increase in lateral strength compared with Specimen #1. Following the peak, the reduction in load capacity occurred at a much slower rate, indicating a more stable post-peak response. Due to concerns regarding potential instability of the test setup, the test was terminated before substantial strength degradation occurred. At the time of termination, the lateral force remained at approximately 90% of the peak value, corresponding to a displacement of 75 mm.

To facilitate comparison of deformation capacity, failure was defined as the point at which the lateral load decreased to 80% of the peak strength. Based on this criterion, Specimen #1 reached failure at a displacement of 47 mm, whereas Specimen #2 sustained lateral loading beyond 75 mm without reaching the defined failure threshold. This indicates that the deformation capacity of Specimen #2 improved by more than 60% relative to Specimen #1.

The enhanced strength and deformation capacity observed in Specimen #2 can be attributed to the improved structural integrity of the UHPC pile shaft, which limited damage development in the socket region and allowed the system to maintain load-carrying capacity at larger deformation levels. These results highlight the effectiveness of using UHPC pile shafts in improving the shear resistance and overall resilience of socket-connected precast bridge substructures.

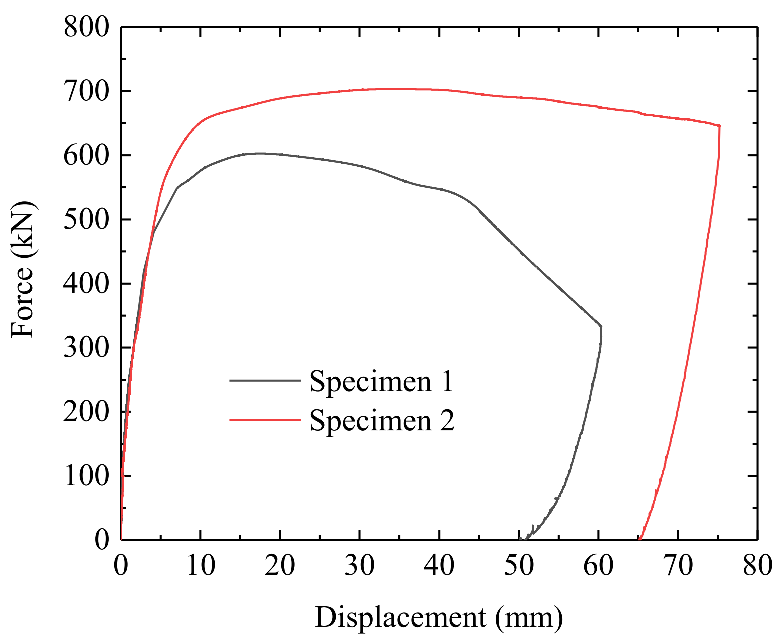

Fig. 4 Lateral load-displacement relationships

3.3 Strain Response of Reinforcement

Strains in the longitudinal reinforcement of the column and the transverse reinforcement of the pile shaft were monitored using strain gauges during testing. The measured reinforcement strains are plotted against the lateral displacement in Fig. 5.

For Specimen #1, the strain in the column longitudinal reinforcement increased rapidly during the early loading stage and was initially higher than the strain recorded in the transverse reinforcement of the pile shaft. As the lateral displacement continued to increase, the strain in the pile shaft reinforcement gradually increased. This trend indicates that the pile shaft began to participate more actively in resisting lateral deformation at larger displacement levels, reflecting increasing demand in the socket region.

Specimen #2 exhibited a different strain distribution pattern. At comparable displacement levels, the strain in the column longitudinal reinforcement was consistently higher than that observed in Specimen #1, indicating greater deformation demand in the column. Meanwhile, the transverse reinforcement in the UHPC pile shaft developed noticeably smaller strains throughout the loading process compared with those measured in Specimen #1. The relatively limited strain development in the pile shaft suggests that the UHPC shaft effectively restrained deformation in the socket region.

The distinct strain responses between the two specimens indicate that the use of UHPC altered the internal force distribution within the system. In Specimen #2, a larger proportion of deformation was accommodated by the column, while the pile shaft experienced comparatively lower strain demand. This redistribution of deformation demand is consistent with the overall structural response observed in the tests and demonstrates the ability of the UHPC pile shaft to maintain its integrity under near-ground lateral loading conditions.

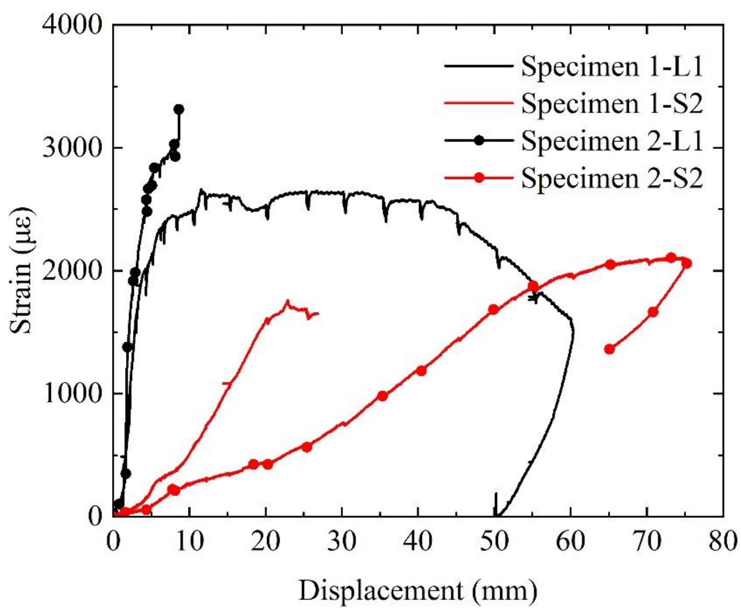

Fig. 5 Reinforcement strain responses

4. Conclusions

This study experimentally investigated the effectiveness of UHPC in improving the structural performance of socket-connected precast column–pile shaft systems under near-ground lateral loading. Two 1/3-scale specimens were tested, differing only in the material used for the pile shaft: normal concrete (NC) in

Specimen #1 and ultra-high-performance concrete (UHPC) in Specimen #2. Based on the experimental observations and test results, the following conclusions can be drawn:

1. Failure mechanisms differed significantly between the two specimens. Specimen #1 exhibited combined damage involving both the pile shaft and the column. Pronounced shaft prying damage occurred in the socket region, characterized by extensive cracking and concrete spalling in the pile shaft, accompanied by flexural damage at the column base. In contrast, the UHPC pile shaft in Specimen #2 remained largely intact, and the majority of damage was concentrated in the column, indicating a more desirable structural response.

2. The use of UHPC in the pile shaft improved the lateral load capacity of the system. Specimen #2 achieved a peak lateral load of 703 kN, which was approximately 17% higher than that of Specimen #1 (602 kN). The UHPC pile shaft effectively resisted the prying forces induced by lateral loading, allowing the system to sustain higher load levels.

3. The UHPC pile shaft significantly enhanced the deformation capacity of the connection system. Based on the criterion that failure occurs when the lateral load decreases to 80% of the peak strength, Specimen #1 failed at a displacement of 47 mm, whereas Specimen #2 sustained lateral loading beyond 75 mm without reaching this limit. This corresponds to an improvement in deformation capacity of more than 60%.

4. Strain measurements indicated a redistribution of deformation demand within the system. The UHPC pile shaft experienced lower transverse reinforcement strains compared with the NC pile shaft, while the column longitudinal reinforcement in Specimen #2 developed larger strains than in Specimen #1. This indicates that the use of UHPC reduced deformation demand in the socket region and shifted the primary deformation toward the column.

Overall, the results demonstrate that replacing conventional concrete with UHPC in the pile shaft can effectively improve the strength, deformation capacity, and damage distribution of socket-connected precast bridge substructures under lateral loading. The findings suggest that UHPC pile shafts provide a promising strategy for enhancing the collision resilience of prefabricated bridge piers.

Acknowledgments

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