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FULL-SCALE EXPERIMENTAL ASSESSMENT OF CONCRETE-FILLED STEEL PIPE PILES SUBJECTED TO SPECIAL LATERAL LOADS IN MSPPP STRUCTURES

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Abstract. Concrete-filled steel pipe piles have been increasingly used in Mono Steel Pipe Pile Pier (MSPPP) structures because of their high strength, ductility, and construction efficiency. Nevertheless, experimental data regarding their resistance to special lateral loads, particularly those induced by vehicular collision, are still limited. This paper presents a full-scale experimental study on the lateral load-carrying capacity of a concrete-filled steel pipe pile representative of an MSPPP configuration. A full-scale static lateral loading test was performed to investigate the pile response under a monotonically increasing horizontal load applied at the pier level. The loading scheme was intended to simulate an equivalent static condition corresponding to vehicular collision actions specified in TCVN 11823:2017. The experimental results indicate that the tested pile sustained a maximum lateral load of 1,275 kN, which is significantly higher than the equivalent static impact load of 720 kN. The pile showed stable flexural behaviour with substantial lateral deformation capacity, without any evidence of local buckling, material fracture, or abrupt loss of load-carrying capacity. These results demonstrate that full-scale static lateral loading tests constitute a practical and reliable method for verifying the resistance of MSPPP piles subjected to special lateral loads and provide useful experimental evidence for structural design and verification.

Keywords: concrete-filled steel pipe pile, MSPPP structure, full-scale experiment, static lateral loading, equivalent vehicle impact load, bridge pier.

1. INTRODUCTION

Concrete-filled steel pipe piles are commonly adopted in modern bridge substructures owing to their high axial and flexural capacity, favourable ductility, and construction efficiency. In recent bridge engineering practice, Mono Steel Pipe Pile Pier (MSPPP) systems where a single large-diameter steel pipe pile simultaneously functions as both pier and foundation have attracted increasing attention. This structural solution offers notable advantages in reducing foundation footprint, shortening construction time, and minimizing environmental impact, while still ensuring adequate load-carrying capacity and structural robustness [1-15].

Notwithstanding these benefits, MSPPP structures are exposed to special lateral loads, among which vehicular collision represents one of the most critical design scenarios. Vehicular collision loads are characterized by their high intensity, short duration, and localized application, which can induce complex structural responses. Existing bridge design codes, such as TCVN 11823:2017 and AASHTO LRFD, generally account for vehicle collision effects through simplified equivalent static forces applied at the pier level. However, these design provisions are largely based on analytical formulations and numerical simulations, and full-scale experimental validation remains scarce, particularly for concrete-filled steel pipe piles used in MSPPP systems [2,3,4].

Most previous studies on vehicle–pier interaction have focused on reinforced concrete piers or multi-column bridge systems, predominantly using numerical simulation approaches [3-9]. Experimental investigations on concrete-filled steel tubular members subjected to lateral impact or equivalent static loading have mainly been limited to component-level or reduced-scale tests, often conducted under idealized boundary conditions [10-12]. While several full-scale lateral loading tests on steel pipe piles have been reported in geotechnical studies [1,13,14], their primary objective was to assess soil–pile interaction rather than to verify structural performance under special lateral loads relevant to vehicular collision.

Furthermore, numerical analyses have indicated that the transformation of dynamic impact loads into equivalent static forces is highly sensitive to factors such as structural stiffness, deformation characteristics, and load application height [5, 15]. Without corresponding experimental calibration, the applicability and reliability of equivalent static approaches for MSPPP structures remain open to question. Consequently, there is a clear engineering demand for full-scale experimental evidence to verify the lateral load resistance of concrete-filled steel pipe piles employed in MSPPP systems.

In this study, a full-scale concrete-filled steel pipe pile representative of an MSPPP structural configuration is experimentally investigated to assess its lateral load resistance. A static lateral loading test was conducted to simulate the equivalent effect of vehicular collision loads specified in TCVN 11823:2017. Numerical simulation was adopted only for preliminary calibration of the target equivalent static load, while the core of the study focused on experimental measurement, observation, and interpretation of the pile's structural response. The findings provide important experimental evidence to support the design verification and practical implementation of MSPPP structures subjected to special lateral loading conditions. Vehicle collisions with bridge substructures are inherently dynamic events involving high strain rates and inertial effects. However, full-scale dynamic impact testing of bridge piers or pile foundations is technically challenging and economically prohibitive. Consequently, equivalent static loading approaches based on displacement-matching or energy-equivalence concepts have been widely adopted to experimentally assess structural resistance under vehicular collision scenarios. Therefore, a static lateral loading approach is employed to represent special lateral loads associated with vehicular collision effects in a practical and conservative manner. Dynamic effects such as strain-rate-dependent material strength enhancement and inertial force redistribution are not explicitly considered in the experimental program. While strain-rate effects generally increase the apparent strength of steel and concrete materials, their omission in static testing may lead to conservative estimates of flexural resistance for bending-dominated responses. This limitation is acknowledged and discussed in the subsequent sections.

2. EXPERIMENTAL PROGRAM

2.1. Concept of the experimental program

The MSPPP system is a slender structural configuration consisting of steel pipe piles without massive footings, which makes it particularly sensitive to horizontal actions such as vehicular collision loads. According to TCVN 11823:2017, the design vehicular collision load acting on bridge piers is specified as 1,800 kN. Conducting direct full-scale impact tests under such loading conditions is technically demanding and economically impractical. For this reason, an equivalent static loading approach was adopted in the present study, in line with common practice in previous experimental investigations on laterally loaded piles [1,15].

In this study, a single concrete-filled steel pipe pile was conceptually isolated from the overall MSPPP system and tested independently under static lateral loading. This testing strategy allows direct verification of the lateral load-carrying capacity of the pile while maintaining consistency with the design collision load specified in the standard. The experimental program was therefore designed to capture the critical structural response of the pile subjected to special lateral loads representative of vehicular collision effects.

The full-scale lateral loading test was conducted in the field on natural ground conditions rather than in a laboratory environment. The pile was embedded to a depth of 13.9 m to replicate the stiffness conditions representative of MSPPP foundations in practical bridge applications.

The embedded length was selected to ensure sufficient mobilization of soil–pile interaction effects during lateral loading, particularly for displacement-based load equivalence. The natural soil strata at the test site provided realistic lateral restraint and stiffness conditions commonly encountered in bridge foundation engineering. Although a detailed geotechnical characterization is beyond the primary scope of this study, the test configuration ensured representative soil–pile interaction behavior.

The ground springs were assumed to follow an elasto–plastic behavior and were modeled using a bilinear skeleton curve based on the upper limit of the horizontal subgrade reaction coefficient. For the elastic stiffness of the ground, use the deformation coefficient E = 2800 N (kN/m2). The internal friction angle (shear resistance angle) φ of sand layers is from 28 to 40.4, cohesive force c of clay layers is 30 kN/m2, and unit volume weight is 18 kN/m3. The maximum N values of the test site ground is 40.

2.2. Load conversion strategy and target load definition

The lateral loading test was designed based on a load conversion procedure from the global MSPPP structural system to a single pile. In this procedure, the vehicular collision load of 1,800 kN specified in TCVN 11823:2017 was first applied to a numerical model of the overall MSPPP structure in order to obtain the corresponding lateral displacement at the pile head level.

Subsequently, a numerical model of a single pile, with geometric and boundary conditions identical to those of the test specimen, was subjected to incremental static lateral loading. The static load that produced the same pile head displacement as that obtained under the 1,800 kN collision force was defined as the equivalent static lateral load for the experimental test. Using this displacement-matching criterion, the target equivalent static load was determined to be approximately 720 kN, as specified in the test plan.

The numerical analysis was employed solely as a preliminary calibration step to identify the appropriate test load level. The primary objective of the study remains the experimental verification of pile behavior and load-carrying capacity under static lateral loading.

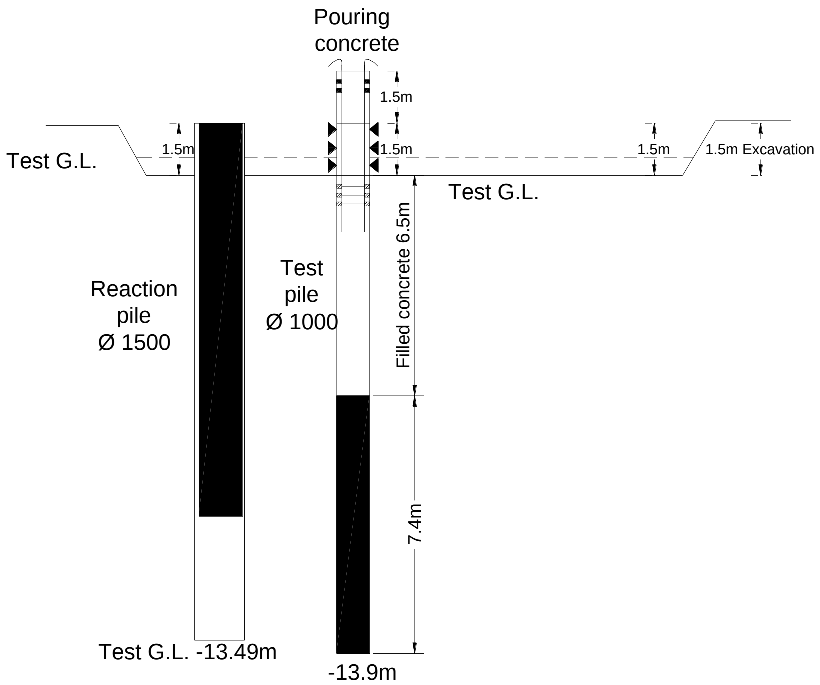


Figure 1. Geometry and configuration of the full-scale concrete-filled steel pipe pile specimen.

2.3. Test specimen and material properties

The test specimen was a full-scale concrete-filled steel pipe pile with the following characteristics (extracted from the test report):

- Outer diameter of steel pipe: 1,000 mm;
- Steel pipe thickness: 16 mm;
- Total pile length: 16.9m;
- Embedded length in ground during test: 13.9m;
- Steel grade: SKK490 (Nominal strength: yield strength YS = 315 MPa, tensile strength TS = 490 MPa; Actual measured strength: YS = 404 MPa, TS = 522 MPa);

- Concrete infill compressive strength (measured): 25MPa.

The steel pipe was filled with cast-in-place concrete prior to testing, forming a composite concrete-filled steel pipe section. The pile configuration represents the pier segment of an MSPPP structure, while the underground portion was designed to replicate the stiffness conditions of the experimental site.

The nominal yield strength of the SKK490 steel specified by the manufacturer is 315 MPa. Material testing conducted prior to the experiment indicated a measured yield strength of 404 MPa. This increase is consistent with the expected material over-strength commonly observed in structural steels due to manufacturing tolerances and strain-hardening effects. The measured value remains within the typical over-strength range reported for SKK490 steel and was therefore adopted in the interpretation of experimental results.

2.4. Test setup and loading arrangement

The full-scale lateral loading test was carried out using a horizontal loading system capable of applying a monotonic static load at the pile head. The lateral load was applied at an elevation corresponding to the pier level of the MSPPP, thereby reproducing the load transfer mechanism associated with vehicular collision actions on bridge piers.

The loading system consisted of a hydraulic jack with a maximum capacity of 5,000 kN, a rigid steel reaction frame securely anchored to the ground, and calibrated load cells installed in line with the jack to measure the applied lateral force. Linear variable displacement transducers (LVDTs) were installed at the pile head and at selected elevations along the pile shaft to record lateral displacements and the deformation profile of the pile.

The applied load acted perpendicular to the pile axis, simulating transverse vehicular impact effects on the pier–pile system in accordance with the equivalent static representation of vehicle collision loads specified in TCVN 11823:2017.

The lateral load was applied through a loading head that allowed rotation during testing. No rotational restraint was imposed at the pile head, and the boundary condition can therefore be classified as a free-head condition, consistent with the flexural behavior of MSPPP piles subjected to lateral loads at the pier level.

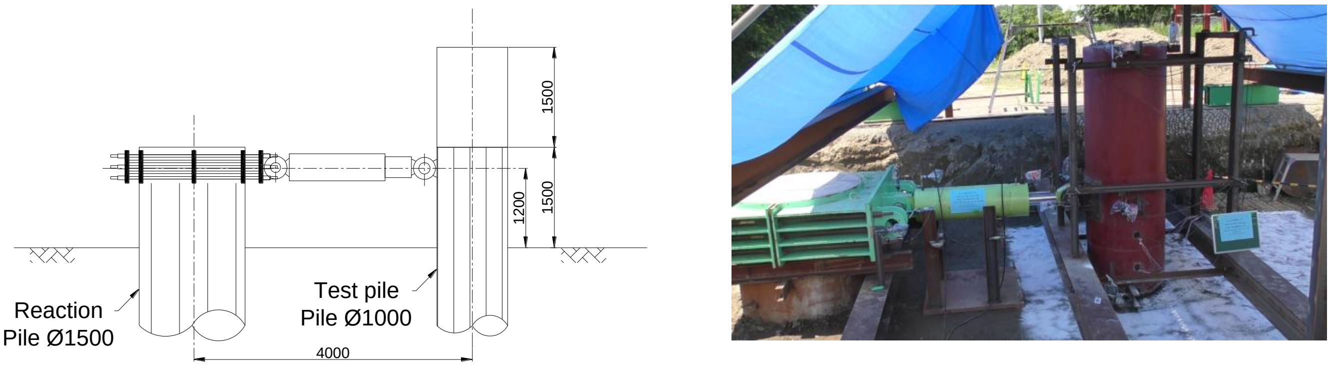


Figure 2. Experimental setup and lateral loading arrangement (Photo taken by research group).

2.5. Loading protocol and measurement scheme

The pile was tested under monotonic incremental lateral loading, with the applied load increased step by step. At each load level, the load was maintained for a specified duration to ensure stabilization of displacement and strain readings prior to the next increment. The loading process continued beyond the target equivalent static load of 720 kN until a maximum applied load of 1,275 kN was reached. The test was terminated based on a predefined displacement limit established by the research team to ensure the safety and stability of the experimental setup. The termination of the test was not governed by the capacity of the hydraulic loading system, but by a predefined displacement limit to ensure experimental safety.

Throughout the loading process, key response quantities including the applied lateral load, pile head displacement, displacement distribution along the pile shaft, and steel pipe strain at critical sections were continuously recorded. Strain gauges were positioned at sections considered critical based on structural judgment and prior numerical analysis.

No unloading was introduced during the test, as the main objective was to assess the ultimate lateral resistance, deformation capacity, and failure characteristics of the pile under special lateral loading conditions representative of vehicular collision effects.

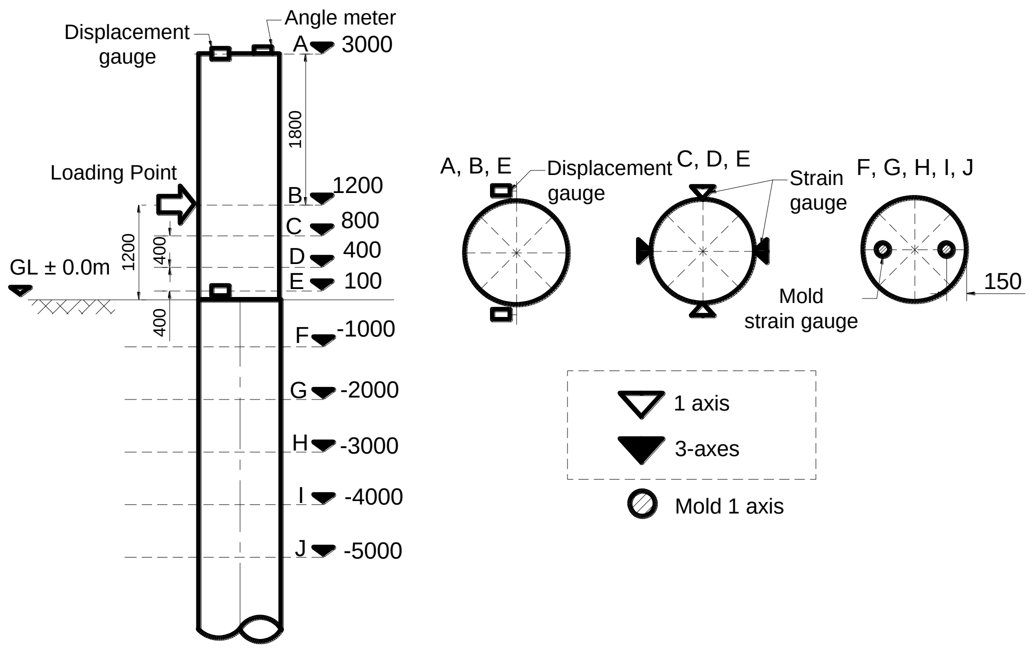


Figure 3. Instrumentation layout and measurement locations.

2.6. Observations during testing

Throughout the test, the pile exhibited a stable lateral load–displacement response without any sudden stiffness degradation or brittle failure. No visible signs of local buckling, cracking, or material fracture were observed in the steel pipe during loading up to the maximum applied load.

Following completion of the test, visual inspection confirmed that the concrete-filled steel pipe pile maintained its structural integrity. The observed deformation was governed by global flexural response.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Global lateral load-displacement response

The global lateral load–displacement response of the pile head is shown in Figure 4, while the corresponding maximum displacement values measured at different locations are summarized in Table 1. The response shows a smooth and continuous trend over the entire loading history, with gradual stiffness reduction and no sudden load drop or instability.

At the equivalent static load level of 720 kN, determined using the displacement-matching procedure corresponding to the vehicular collision load specified in TCVN 11823:2017, the pile response remained stable and within the pre-yield deformation range. At this load level, no evidence of abrupt stiffness degradation or nonlinear instability was observed.

The test was further continued until a maximum applied lateral load of 1,275 kN was reached, at which the pile still maintained its load-carrying capacity with controlled deformation. This maximum load corresponds to approximately 1.77 times the equivalent static impact load, indicating a substantial margin between the design-level demand and the experimentally verified capacity. The pile head displacement was evaluated as the average value of the measured displacements on the north and south sides of the pile. At the maximum load, the displacement at the loading point was approximately 100 mm.

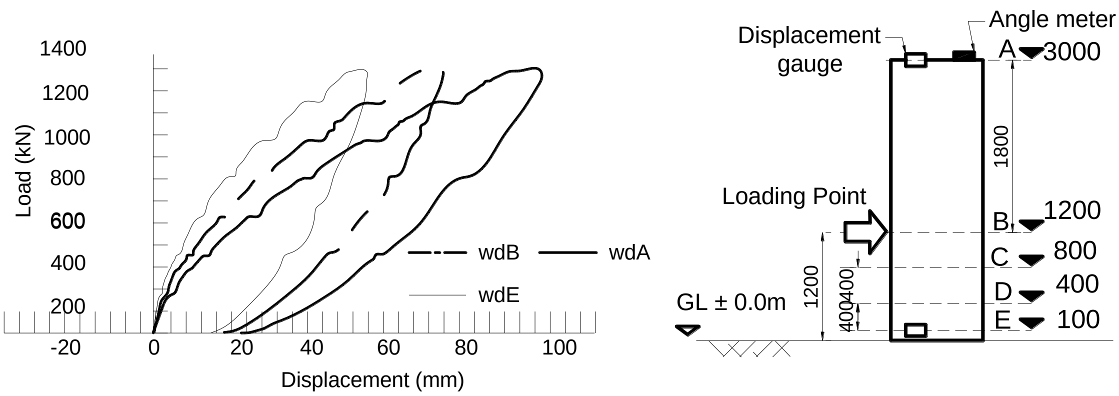


Figure 4. Load and Displacement.

Table 1. Max displacement.

Name	Dimension	Max displacement (mm)
wdA	A	123.3
wdB	B	92.1
wdE	E	68.1

3.2. Characteristic load levels and quantitative response

To facilitate quantitative interpretation of the experimental results, several representative load levels along the lateral load–displacement curve were identified, including the equivalent static impact load and the maximum applied load. The corresponding pile responses at these load levels are summarized in Table 2.

Table 2. Summary of the lateral load levels and corresponding pile responses.

Load level	Lateral load (kN)	Pile head displacement (mm)	Structural response
L1	125	10	Linear elastic response
L2 (equivalent impact)	720	32	Stable response, no yielding
L3	937.5	92.1	Progressive stiffness degradation
L4 (maximum load)	1,275	123.3	Large deformation, stable behavior

The absence of any abrupt increase in displacement or loss of load-carrying capacity across these load levels indicates a ductile lateral response, which is consistent with observations reported in other full-scale lateral loading tests on steel pipe piles [1,15].

3.3. Deformation pattern and failure characteristics

Throughout the test, the pile response was dominated by global flexural bending of the concrete-filled steel pipe pile. Up to the maximum applied load, no evidence of local buckling of the steel pipe wall, cracking-induced localization, or sudden failure was observed.

Post-test visual inspection confirmed that the pile maintained its structural integrity along the tested length. The deformation pattern suggests that flexural action governs the response, rather than material rupture or local instability. This behavior demonstrates the beneficial role of composite action between the steel pipe and the concrete infill in improving deformation capacity under lateral loading, in agreement with previous experimental observations on concrete-filled steel tubular members [11,12]. Figure 5 shows the condition of the pile before testing and the deformation profile after completion of the lateral loading test.

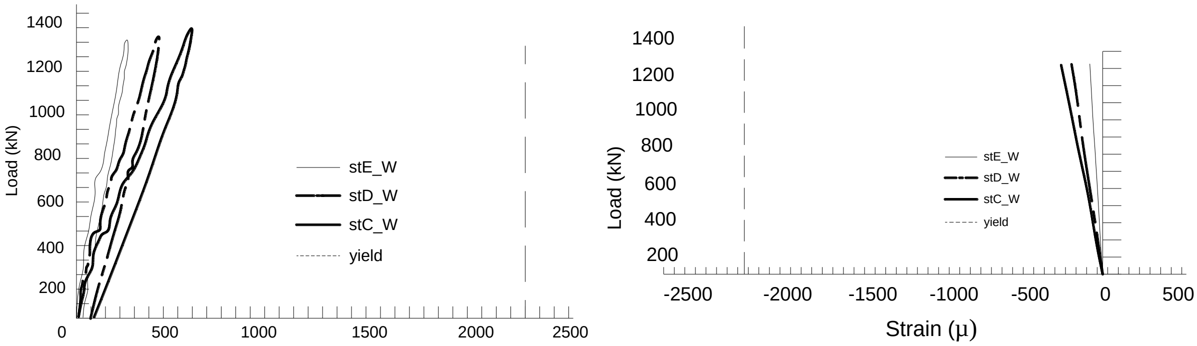
Before testing　　　After testing

Figure 5. Pile condition before testing and deformation profile after the lateral loading test (Photo taken by research group).

3.4. Strain response and material performance

Strain measurements obtained from the steel pipe provide further insight into the material response under increasing lateral load. Recorded strain values at critical sections remained below the yield strain of the steel material throughout the test, including at the maximum applied load of 1,275 kN.

The absence of steel yielding corroborates the visual observations and confirms that the pile response was governed by flexural deformation capacity rather than material failure. This result demonstrates that the tested pile configuration possesses adequate strength and stiffness to resist special lateral loads without entering an undesirable inelastic material regime.



(Tension side) (Compression side)

Figure 6. Measured strain response of the steel pipe at selected load levels.

3.5. Consistency with preliminary numerical calibration

The preliminary numerical analysis conducted prior to the full-scale test was employed solely to estimate the equivalent static load corresponding to the design vehicular impact action through a displacement-matching approach. The numerical model was not intended to reproduce the full experimental response nor to investigate detailed dynamic effects.

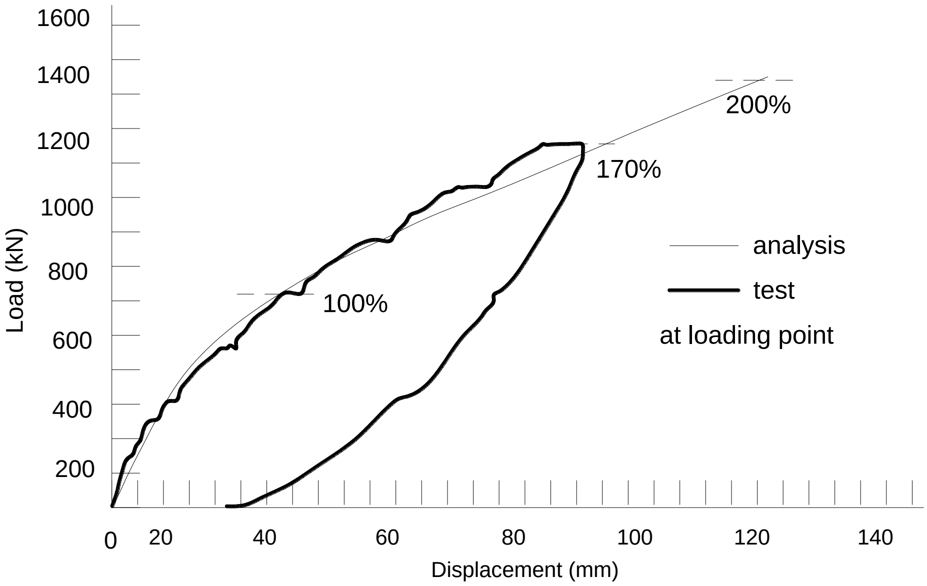


Figure 7. Comparison between experimental results and numerical analysis of the load -displacement response at the loading point.

At the equivalent static load level of 720 kN, the experimentally measured pile head displacement was found to be consistent with the displacement predicted by the preliminary numerical calibration. This agreement confirms that the selected equivalent static load reasonably represents the target impact scenario in terms of global lateral deformation demand.

It should be emphasized that numerical simulation in this study served only as a supporting tool for load calibration. The primary contribution of the research lies in the full-scale experimental observations, which provide direct evidence of the lateral load-carrying capacity and deformation characteristics of concrete-filled steel pipe piles in MSPPP structures. A qualitative comparison between the experimental and the numerically estimated load–displacement responses at the loading point is presented in Figure 7.

3.6. Implications for MSPPP structural verification

The experimental results demonstrate that the tested concrete-filled steel pipe pile with a diameter of 1.0 m can sustain lateral loads significantly higher than the equivalent static load associated with vehicular collision actions. The confirmed reserve capacity, together with the stable deformation behavior observed throughout the test, highlights the inherent robustness of MSPPP pile components when subjected to special lateral loads.

From a structural verification standpoint, these findings indicate that full-scale static lateral loading tests can serve as a reliable and economical alternative to direct impact testing for evaluating the resistance of MSPPP structures. By directly capturing the load–displacement response and deformation characteristics under representative loading conditions, such tests provide meaningful experimental evidence for assessing structural safety and performance.

Overall, the experimental evidence presented in this study offers valuable support for the design verification and safety assessment of MSPPP systems subjected to vehicular collision effects and contributes to a more rational application of equivalent static approaches in engineering practice.

4. CONCLUSION

Based on experimental observations and subsequent analysis, the following conclusions can be drawn:

- The equivalent static lateral load corresponding to the design vehicular collision force of 1,800 kN was determined to be approximately 720 kN using a displacement-matching procedure. This load level was successfully applied and verified through full-scale static lateral loading tests.

- The tested concrete-filled steel pipe pile with a diameter of 1.0 m sustained a maximum lateral load of 1,275 kN, which is approximately 1.77 times the equivalent static impact load. Throughout the test, the pile exhibited stable load–displacement behavior without any sudden loss of stiffness or load-carrying capacity.

- No local buckling, steel yielding, or material fracture was observed up to the maximum applied load. Both strain measurements and post-test inspection confirmed that the pile response was governed by global flexural deformation rather than material failure.

- The experimentally measured pile head displacement at the equivalent static load showed good agreement with the results obtained from the preliminary numerical calibration, supporting the applicability of the displacement-matching approach for converting vehicular impact loads into equivalent static loads for experimental verification.

- The results demonstrate that full-scale static lateral loading tests provide a practical, reliable, and economical method for verifying the resistance of MSPPP piles subjected to special lateral loads, offering a viable alternative to direct impact testing.

It should be noted that the experimental program adopted a static loading approach to represent special lateral loads associated with vehicular collision. Dynamic effects, including strain-rate-dependent material behavior and inertial force redistribution, were not explicitly captured in the test. For steel and concrete materials, strain-rate effects generally lead to increased apparent strength, suggesting that the static test results may provide conservative estimates of flexural resistance. Nevertheless, certain dynamic failure mechanisms, such as localized shear effects, cannot be fully represented by static testing. Further investigations incorporating dynamic testing or advanced numerical analyses are recommended.

Overall, the experimental evidence presented in this study provides valuable data for the structural verification of MSPPP systems under vehicular collision effects and supports the use of full-scale static testing as an effective tool for bridge pier design and safety assessment.

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