Research on Reinforcement Method for Missing Anchor Bolts of Bridge Pot Bearings Based on Structural Adhesive Bonding Technology in Narrow Space

Junwei Liang[1,*], Yufeng Ying[2], Peng Jiang[2], Kun Jiang[1]

[1]Zhejiang Jiaogong High-Level Highway Maintenance Co., Ltd., Hangzhou, 310051, China
[2]Zhejiang Zhoushan Cross-sea Bridge Co., Ltd., Zhoushan, 316033, China
*Corresponding author's e-mail: l_jw1988@qq.com

Abstract. The loss of anchor bolts in pot bearings significantly affect bridge structural safety. Taking a ramp bridge as the engineering background, this paper conducts theoretical analysis and reinforcement scheme research on the problem of missing anchor bolts in pot bearings in narrow space. finite element simulation is used to analyze the stress characteristics of bearings under multiple load combinations, revealing that bolts mainly serve as structural fixing components. The bearing capacities of three failure modes of post-installed anchor bolts are calculated, determining that concrete edge failure is the controlling mode, with a design shear capacity of 27.6 kn for a single M20 bolt. Based on scheme comparison, a channel steel-structural adhesive composite reinforcement system based on the equal-strength replacement principle is proposed. Theoretical calculations confirm that the adhesive action of steel plates can achieve a functional equivalent replacement for a single bolt. Engineering practice shows that in narrow spaces, the total cost of using this scheme is only 13.8% of the traditional bearing replacement scheme, with the advantages of convenient construction and not affecting traffic, providing a reference for the treatment of similar bridge bearing diseases.

Keywords: narrow space; pot bearing; anchor bolt; structural adhesive bonding; reinforcement technology

1 Introduction

Bridge bearings, as key load-transfer components connecting superstructure and substructure, bear the important functions of transmitting vertical loads, accommodating horizontal displacements, and structural rotation. With a large number of bridges entering the mid-to-late operational period, bearing defects have become increasingly prominent. According to inspection data from 19 expressway bridges and 5 high-speed railway bridges in Eastern China, among 10,486 bearings examined, the main defects of pot bearings and spherical bearings include bolt corrosion, rubber aging, and steel pot deformation, among which anchor bolt corrosion and loss is one of the most common defect types [1].

© The Author(s) 2026
H. Wu et al. (eds.), *Proceedings of the 2026 3rd International Conference on Civil Engineering Structures and Concrete Materials (CESCM 2026)*, Advances in Engineering Research 312,
https://doi.org/10.2991/978-94-6239-865-8_2

Pot bearings have been widely applied in highway bridges due to their advantages of high bearing capacity and flexible rotation. However, under adverse conditions such as marine environment and de-icing agent erosion, anchor bolts of bearings are prone to electrochemical corrosion, leading to cross-sectional reduction and even fracture. Recent studies have established time-dependent reliability models for bearing anchor bolts considering chloride ion diffusion, revealing the degradation law of anchor bolt bearing capacity due to corrosion [2]. Research on post-installed anchors has shown that concrete edge failure often becomes the controlling factor when edge distance is small [3,4]. Machine learning approaches have been successfully applied to predict the shear capacity of post-installed anchors, achieving high accuracy in bearing capacity estimation [5].

Regarding bonded reinforcement, externally bonded steel plate reinforcement technology has developed rapidly in recent decades [6]. Studies on steel-concrete interface bonding have revealed that appropriate surface treatment can significantly improve bond strength [7,8]. Recent research on collaborative interfacial shear capacity demonstrates that combined adhesive bonding and mechanical anchoring systems can effectively enhance the load-bearing performance of steel plate-concrete interfaces [9].

In recent years, high-performance structural adhesives have made significant breakthroughs in marine engineering. Bioinspired adhesives, inspired by organisms such as mussels, have developed rapidly. Advanced epoxy adhesive systems have shown excellent durability in marine environments, with comprehensive characterization studies confirming their mechanical stability under seawater exposure [10]. Jilin University synthesized ESO-Am materials using epoxy soybean oil, achieving an underwater bonding strength of 5.2 MPa, with strength retention exceeding 93% after soaking in seawater for 30 days [11]; Oak Ridge National Laboratory developed a recyclable adhesive (TCD-V) from waste PET, with an underwater lap shear strength of 6.51 MPa, and it can be debonded and reused at low temperatures [12]. Real wave erosion tests confirmed their continuous adhesion ability for up to one year. These technologies are gradually replacing welding/riveting, being applied in the fixation of offshore wind power sensors and the installation of ship structural components, showing great potential in critical load-bearing marine parts.

Existing research mainly focuses on complete bearing replacement, while research on in-situ reinforcement technology for local defects of existing bridge bearings is relatively scarce. Under conditions of limited space and inconvenient disassembly, how to effectively treat missing anchor bolts still lacks systematic theoretical analysis and engineering practice. This paper takes a ramp bridge as the engineering background, proposes a reinforcement scheme based on structural adhesive bonding technology through finite element analysis and theoretical calculation, aiming to provide a reference for similar engineering projects.

2 Engineering Overview

Zhoushan Cross-sea Bridge is an important transport hub connecting Zhoushan Archipelago with mainland China, consisting of Jintang Bridge, Xihoumen Bridge,

Taoyao Gate Bridge, Xiangjiaomen Bridge, and approach works. Cezi B ramp bridge is located in the Cezi interchange area of Xihoumen Bridge, with a span arrangement of 5×16.705 m, 1 continuous 5-span reinforced concrete box girder, C40 concrete strength, and 8.5 m bridge deck width. Bearings adopt GPZ(II) pot bearings, including fixed bearings (GD), unidirectional bearings (DX), and bidirectional bearings (SX).

According to annual regular inspection reports, bearing defects have shown a trend of gradual deterioration. In January 2024, inspection found that among 14 bearings, a total of 16 bolts were missing, mainly distributed at piers 0#, 3#, and 5#. The missing bolts are shown in Figure 1. Defect characteristic analysis shows: (1) bolts missing from lower bearing plates exceed those from upper plates, possibly related to higher humidity and chloride ion enrichment at the cap beam location; (2) pier 5# has the most severe defects, related to its proximity to the seaward side and harsh environmental conditions. Due to the lack of consideration for subsequent maintenance needs during the early construction process, the minimum clearance distance between the upper and lower bearings of this ramp bridge is 11.5cm. This clearance is insufficient to provide the minimum working space for the use of specialised equipment. An alternative solution suitable for narrow working spaces needs to be proposed for this special condition. The field spatial relationship of basin bearing was shown in figure 2, The on-site condition of the bearing with missing bolts is shown in Figure 3.

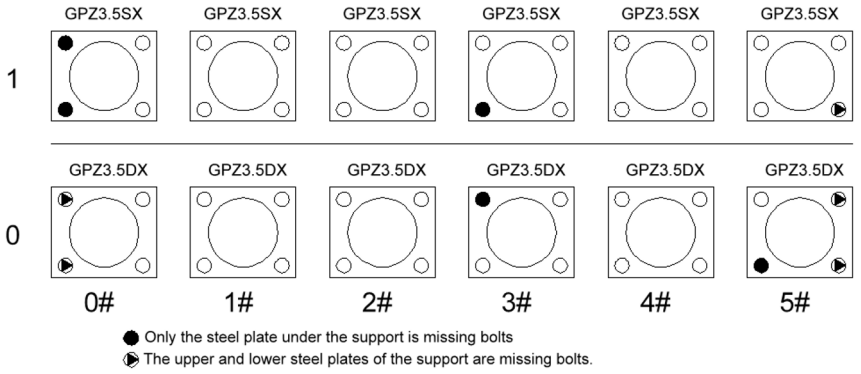


Fig. 1. Distribution map of bearing and bolt missing parts

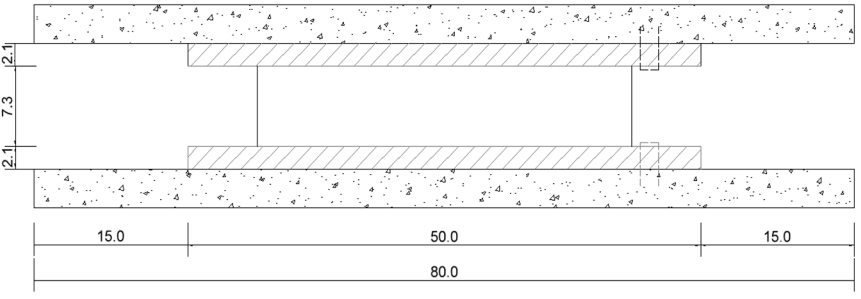


Fig. 2. Field spatial relationship diagram of basin bearing



Fig. 3. A bearing with missing bolts

3 Finite Element Analysis

3.1 Model Establishment

A three-dimensional finite element model was established using Midas Civil 2021. Box girders were simulated using beam elements with actual cross-sectional dimensions input; bearings were simulated using elastic connection elements with stiffness parameters set according to bearing types; piers were simulated using beam elements, and pile foundations using elastic supports. The model contains 184 nodes, 164 elements. Material parameters were taken from design documents: C40 concrete elastic modulus 3.45×10^4 MPa, unit weight 25 kN/m³. The finite element model diagram is shown in Figure 4.

Load cases were considered according to General Specifications for Design of Highway Bridges and Culverts (JTG D60-2015)[13]: dead load, live load (Highway-I lane load), temperature load (overall temperature rise +20°C and fall -20°C), uneven settlement of 5 mm at bearings, and shrinkage and creep effects.

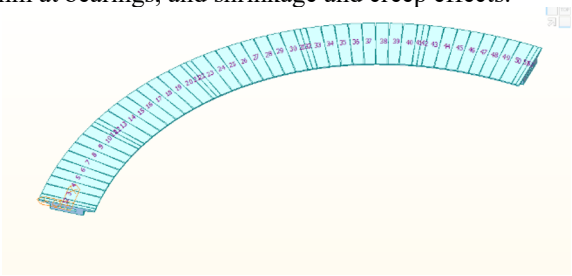


Fig. 4. Finite Element Model of the Ramp Bridge

3.2 Calculation Results

Calculation results show that under dead load, the maximum vertical reaction force of bearings is 1,983 kN, occurring at the fixed bearing of pier 3#; under standard load

combination, the maximum horizontal reaction force is 380 kN, occurring under temperature load case. Take the bearing friction coefficient as 0.3[14]:

$$f=\mu \cdot F_N=0.3\times 1983=595kN$$

Since f = 595 kN > 380 kN, this indicates that under normal service conditions, horizontal forces are primarily borne by the friction force between bearing steel plates and concrete bearing seats, while bolts mainly serve as structural fixing and positioning components. Parametric sensitivity analysis of temperature effects shows: when temperature change increases from ±10°C to ±30°C, bearing horizontal reaction force increases from 210 kN to 550 kN, showing an approximate linear relationship; when friction coefficient increases from 0.2 to 0.4, friction resistance increases from 396 kN to 793 kN. Temperature effects and friction coefficient are key factors affecting bearing forces.

4 Bearing Capacity Analysis of Anchor Bolts

4.1 Failure Modes and Calculation Methods

According to established anchor theory [4], post-installed anchors under shear force exhibit three main failure modes: anchor steel shear failure, concrete edge failure, and concrete shear pry-out failure. Anchor steel shear failure occurs when edge distance is large and embedment depth is sufficient, with bearing capacity: $V_s=n\cdot A_s\cdot f_{vk}$. Concrete edge failure occurs when anchors are close to concrete edges, with bearing capacity dependent on edge distance, concrete strength, and anchor diameter: $V_{Rk,c}=\alpha \cdot d_0^{\beta}\cdot \sqrt{f_{cu,k}}\cdot c_1^{1.5}$. Concrete shear pry-out failure is related to concrete tensile capacity: $V_{Rd,cp}=k_1\cdot N_{Rk,c}/\gamma_{Rcp}$

4.2 Bearing Capacity Calculation

The specifications of bearing anchor bolts are M20 (grade 8.8), effective cross-sectional area A_n = 245 mm², embedment depth h_ef = 200 mm, edge distance c_1 = 200 mm, and concrete strength C40.

Steel shear failure capacity: The design shear strength of grade 8.8 bolts f_v = 320 MPa, calculated as: $V_s=78.4kN$

(1)Concrete edge failure capacity: Since edge distance c_1 = 200 mm < max($10h_{ef}$, 60d) = 2,000 mm, edge effect must be considered. Considering edge distance correction coefficient 0.9, reinforcement effect coefficient 1.4, etc., after calculation of various parameter values: $V_{Rd}=27.6kN$

(2)Concrete shear pry-out failure capacity: $N_{Rk,c}=k_2\cdot \sqrt{f_{cu,k}}\cdot h_{ef}^{1.5}$, substituting values: $V_{Rd,cp}=k_1\cdot N_{Rk,c}/\gamma_{Rcp}=144.5kN$

4.3 Bearing Capacity Control Value

According to specifications[15], the minimum value of all failure modes is taken: V_d= min (78.4,27.6,144.5)=27.6kN.

The design shear capacity of a single M20 anchor bolt is 27.6 kN, controlled by concrete edge failure mode. When edge distance is small, concrete edge failure often becomes the controlling factor, consistent with research findings [3,4]. Under extreme conditions, assuming a single bearing's 8 bolts uniformly bear horizontal force of 380 kN, each bolt bears 47.5 kN. If 1 bolt is missing, remaining 7 bolts each bear 54.3 kN, exceeding the design capacity of 27.6 kN, indicating safety hazards exist after bolt loss, requiring reinforcement treatment.

5 Reinforcement Scheme Design

5.1 Reinforcement Principle

Based on the equal-strength replacement principle, channel steel components are bonded to bearing pedestals using structural adhesive, utilizing the shear bonding capacity of the adhesive to replace the anchoring function of missing bolts. The load transfer path of the reinforcement system is: bearing steel plate → structural adhesive → channel steel → tension rods → channel steel → structural adhesive → concrete pedestal, where structural adhesive bears shear stress and tension rods bear tensile and shear stresses.

Based on the principle of equal strength replacement, the channel steel components use structural adhesive with bearing pads, utilizing the shear bearing capacity of the adhesive to replace the anchoring function of the missing bolts. The force transmission path of the reinforcement system is: bearing steel plate → structural adhesive → channel steel → tie rod → channel steel → structural adhesive → concrete pedestal, where the structural adhesive bears shear stress and the tie rod bears tensile and shear stress. The strengthening scheme of bonding steel plates and channel steel with structural adhesive is illustrated in Fig. 5.

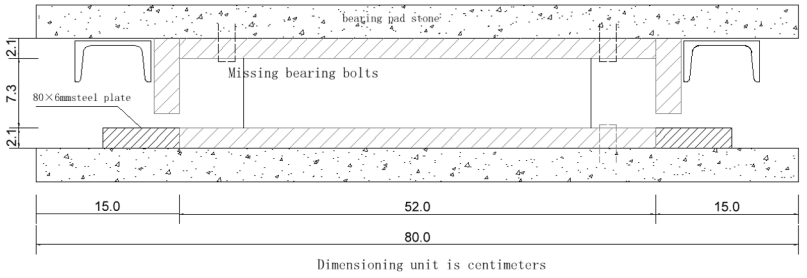


Fig. 5. Reinforcement scheme of structural adhesive bonded steel plate channel steel

The field survey confirmed that the clearance height of the target area was only 7.1 cm. Restricted by the narrow installation space, the original bearing fracture bolt re-

mained inside the concrete anchoring matrix, and the conventional machinery could not be implemented due to the lack of working space.

In the comparison scheme, the traditional processes such as the limit device and the chemical anchor bolt implantation have higher requirements on the construction clearance. The existing working conditions cannot meet the layout space of the power tools required for drilling, implantation and fastening, and there are significant applicability defects in this working condition. In addition, although fiber reinforced polymer has high strength characteristics, the thickness of its plate section is limited, resulting in insufficient shear capacity in the thickness direction of its anisotropic characteristics. In the absence of mechanical anchorage, it is difficult for FRP materials to provide sufficient shear restraint by their own stiffness to curb the displacement trend of the bearing.The scheme of pasting steel plate and channel steel not only has concise construction process, strong geometric adaptability to complex interfaces, but also has better comprehensive cost-effectiveness under the premise of meeting structural safety. It is the optimal technical path for bridge bearing reinforcement under this working condition.

5.2 Material Selection

Structural adhesive selected is modified epoxy resin adhesive. It should meet Grade A adhesive performance[13]: tensile strength ≥30 MPa, steel-to-steel shear strength ≥15 MPa, bond strength with concrete ≥2.5 MPa. Measured values are 35.2 MPa, 17.8 MPa, and 3.1 MPa respectively, all meeting requirements. Channel steel uses No. 8 hot-rolled channel steel, and tension rods use 20 mm diameter Q235 round steel.

5.3 Bonding Area Calculation

According to the equal-strength replacement principle, the shear stress on the bonding interface must satisfy:

$$\tau = V_d / A_g \leq f_{go}$$

Taking steel-concrete bond strength design value f_{go} = 1.05 MPa for C30 concrete, considering construction quality reduction coefficient η = 0.95, effective bond strength $f_{go,eff}$ = 0.998 MPa, required bonding area: $A_g \approx 277 cm^2$

Considering safety margin, take A_g = 300 cm². Channel steel bottom plate width b = 8 cm, required bonding length L = 300/8 = 37.5 cm, designed as L = 38 cm, with bonding on both sides, single-side length 19 cm. For multiple missing bolts, bonding area increases proportionally: 600 cm² for 2 missing bolts, 1,200 cm² for 4 missing bolts.

5.4 Structural Design

Channel steel tension-rod structure is suitable for situations with sufficient space above bearings: No. 8 channel steel is arranged along longitudinal bridge direction on both sides of bearings, channel steel bottom plates bonded to pedestals, length exceeding bearing steel plates by 5 cm on each side; tension rods pass through channel steel webs, contact surfaces ground flat, tightly contacting bearing steel plates; rod ends fixed with nuts and washers, tightening torque controlled at 80~100 N·m.

U-shaped steel plate structure is suitable for situations with limited space below bearings: U-shaped steel plate is welded from 8 mm thick steel plates, bottom plate width 80 mm, side plate height 60 mm, side plates bonded to cap beam sides, bottom plate bonded to cap beam top surface.

5.5 Tension Rod Verification

After grinding treatment of tension rod contact surfaces, grinding area $A_{contact}$= 288 mm². For the case of 2 missing bolts, rods bear shear force of 55.2 kN. Shear stress:τ=95.8MPa

Q235 steel design shear strength f_v = 120 MPa, satisfying requirements. Rod total tensile force considering pretension 22.5 kN and temperature additional tensile force 2.3 kN, totaling 24.8 kN, tensile stress 79.0 MPa, less than Q235 design tensile strength 205 MPa, verification passed.

5.6 Durability Design

Steel components must reach Sa2.5 grade, coating system: epoxy zinc-rich primer (60 μm) + epoxy micaceous iron oxide intermediate paint (80 μm) + polyurethane topcoat (60 μm), total dry film thickness ≥200 μm, meeting C4 corrosion environment requirements. Protective coating applied to exposed surfaces of adhesive after curing. According to recent durability studies [10], epoxy resin adhesive bonding systems can maintain effective performance for over 20 years under normal environmental conditions; for this marine environment project, it is recommended to conduct special inspections every 5 years.

6 Construction Technology

Construction technology flow: surface treatment → adhesive preparation → bonding and installation → curing → corrosion protection.

For surface treatment: after removing loose and deteriorated parts from concrete pedestal surfaces, use angle grinder with steel brush to chisel along force direction with depth of 1~2 mm, blow away dust with blower, and wipe with acetone. Steel component bonding surfaces are ground with grinding wheel to reveal metallic luster, grinding pattern perpendicular to force direction. Research shows appropriate surface treatment can improve bond strength by 20%~30%.

Structural adhesive is mixed in A:B = 2:1 (mass ratio), electrically stirred for 3-5 minutes until uniform color, mixing quantity should be used within 30 minutes. For bonding, uniformly apply adhesive to concrete surface and channel steel bottom plate with thickness of 3-5 mm, thicker in middle and thinner at ends, ensuring adhesive fully flows during pressing. Curing conditions: at normal temperature 20°C, cure for 7 days to reach 80% of design strength, avoid vibration and impact during curing period.

In March 2024, the reinforcement treatment was implemented for 16 missing bolts according to this scheme, completed in 12 days without interrupting traffic. Environmental temperature was 15~25°C, relative humidity 60%~75%, meeting construction requirements. Pull-out test after adhesive curing showed bond strength of 2.8 MPa, failure surface in concrete interior, verifying construction quality.

7 Conclusion

This paper systematically studied theoretical analysis and reinforcement technology for missing anchor bolts of bridge pot bearings, with main conclusions as follows:

(1) Finite element analysis revealed bearing force characteristics: under normal service conditions, bearing friction resistance 595 kN exceeds horizontal force 380 kN, horizontal forces are primarily borne by friction, bolts mainly serve as structural fixing components; temperature effect is a key factor affecting bolt forces.

(2) Based on post-anchor theory, calculated three failure modes' capacities of M20 anchor bolts, identifying concrete edge failure as controlling mode, with design shear capacity of 27.6 kN per bolt.

(3) Six months of monitoring data after construction showed reinforcement component strain stable, bonding interface intact, verifying effectiveness and reliability of the scheme.

References

1. Ma F B, Zhang L, Cui M D, et al. Investigation and treatment of bearing diseases for typical expressway and high-speed railway bridges in Eastern China: a field practice campaign[J]. Structure and Infrastructure Engineering, 2024, 20(1): 45-62.
2. Li X, Wang Z, Chen Y. Load capacity prediction of corroded steel plates reinforced with adhesive and high-strength bolts using a particle swarm optimization machine learning model[J]. Buildings, 2024, 14(8): 2351.
3. Tian Y, Zhang H, Liu W. Aggregate type and concrete age effects on anchor breakout performance: large database and insights[J]. Applied Sciences, 2024, 14(5): 2122.
4. Eligehausen R, Mallée R, Silva J F. Anchorage in Concrete Construction[M]. Berlin: Ernst & Sohn, 2006.
5. Mansouri I, Hu J W, Kisi O. Prediction accuracy of random forest, XGBoost, LightGBM, and artificial neural network for shear resistance of post-installed anchors[J]. Structures, 2023, 50: 1252-1264.
6. L'Hermite R. L'application des colles et résines dans la construction[J]. Annales de l'Institut Technique du Bâtiment et des Travaux Publics, 1967, 20(231-232): 89-103.

7. Oehlers D J, Moran J P. Premature failure of externally plated reinforced concrete beams[J]. Journal of Structural Engineering, 1990, 116(4): 978-995.
8. Wang Y, Li H, Zhang X. Experimental study on the bonding performance between shaped steel and high-strength concrete[J]. Buildings, 2024, 14(6): 1639.
9. Liu Z, Chen S, Wang J. Collaborative interfacial shear capacity of adhesive bonding and novel shooting nail for steel plate strengthening concrete structures[J]. Scientific Reports, 2024, 14: 82801.
10. Fernández-Viña M, Otero F, Freire L, et al. Characterization of epoxy adhesive for marine applications[J]. Oceans, 2024, 5(4): 52.
11. Gao X, Fang X, Wang H, et al. Fully erasable amphibious adhesives derived from soybean oil with record-high underwater adhesion strength[J]. Advanced Materials, 2025, 37(47): e07894.
12. Danielson M K, Sumpter B G, Demchuk Z, et al. High-performance reversible adhesive from PET waste for underwater, structural, and pressure-sensitive applications[J]. Science Advances, 2025, 11(30): eadw1288.
13. Ministry of Transport of the People's Republic of China. General Specifications for Design of Highway Bridges and Culverts: JTG D60-2015[S]. Beijing: China Communications Press, 2015.
14. Ministry of Transport of the People's Republic of China. Pot Bearings for Highway Bridges: JT/T 391-2009[S]. Beijing: China Communications Press, 2009.
15. Ministry of Housing and Urban-Rural Development of the People's Republic of China. Technical Specification for Post-installed Fastenings in Concrete Structures: JGJ 145-2013[S]. Beijing: China Architecture & Building Press, 2013.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (http://creativecommons.org/licenses/by-nc/4.0/), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

