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Rehabilitation of corroded H-piles using friction-type bolted plate-based repair system

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ABSTRACT

This paper presents the details of an experimental and numerical study that was conducted to evaluate the effectiveness of a friction-type bolted steel plate-based system for underwater rehabilitation of steel H-piles with severe but localized corrosion. The repair system allows the applied axial load to be transferred from the original pile to the steel repair plates through friction at the interface between the pile flanges and the steel repair plates. To evaluate the performance of the repair system, seven 4.57 m-long HP12 × 53 (U.S. designation) piles were deteriorated to simulate corrosion of the flange and web. The piles were repaired using friction-type bolted steel plates and tested under axial compression to investigate the behavior of repaired piles. The test results demonstrated the effectiveness of the proposed repair system in terms of restoring the axial stiffness and capacity of the deteriorated piles. A rational approach for the design of the friction-type steel plate-based repair system is also summarized. A FE model was developed to simulate the repaired piles. Validated by the full-scale experimental results of seven retrofitted piles, the numerical model was used for a parametric study to investigate different factors that might affect the axial capacity of the strengthened piles. The research findings demonstrate that the proposed friction-type steel plate-based repair system can be easily used to restore the capacity of steel H-piles with severe but localized corrosion.

1. Introduction

Steel H-piles have been used to support a wide range of structures including bridges, wharfs, and oil platforms. Based on field observations conducted by the authors, these piles have suffered severe but localized corrosion within 1 m of the water or soil level as shown in Fig. 1. Traditional rehabilitation approaches involve welding steel plates or sections to the original pile to compensate for the loss of section. However, this approach often requires dewatering which is costly and time consuming. Underwater welding techniques are also available [1,2], however these often require specialized equipment, training and inspection methods. As such, underwater welding is more commonly used for repairs of specialized or critical structures such as nuclear powerplant components, offshore structures, and pipelines. The use of externally bonded fiber reinforced polymer (FRP) sheets and plates has been investigated as an alternative approach to repair steel compression members due to their high strength-to-weight ratio, corrosion resistance, and ease of application [3–9]. Shaat and Fam [5] investigated the behavior of 27 short and 5 long square hollow section columns strengthened with carbon FRP (CFRP) sheets. The short columns had slenderness ratios less than 5 and failed by local buckling while the long columns had slenderness ratios of 68 and failed by global buckling. The study investigated the influence of the type of CFRP, fiber orientation, and number of layers on the behavior of the strengthened columns. The results indicated that CFRP increased the axial capacity of short and long square hollow columns and that transversely wrapped FRP was more efficient than FRP oriented in longitudinal direction for short columns. Teng and Hu [8] studied the use of Glass FRP (GFRP) jackets to strengthen circular hollow steel tubes under axial compression both experimentally and numerically. The researchers tested four steel tubes with and without GFRP jackets and found that the GFRP jackets increased the ultimate load by 5–10% and increased the ductility of circular hollow steel tubes by 10 times. Furthermore, the numerical simulation results indicated the effectiveness of using FRP jackets to strengthen thin cylindrical shells under combined axial compression and internal pressure. Young et al. [9] and Silvestre et al. [7] carried out both experimental and numerical investigations on lipped channel columns strengthened by CFRP. The studies indicated that longitudinally oriented CFRP was more effective than transversely oriented CFRP to increase ultimate capacities of short columns due to the nature of the column critical buckling mode. The increment of ultimate capacity was proportional to the number of layers of CFRP. Kim and Harries [4] strengthened steel T-section compression struts with

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Fig. 1. Localized corrosion of H-piles from field visit.

CFRP strips and tested them in axial compression. The results indicated that the CFRP strips effectively reduced the stresses at the web-flange junction. It was revealed that increasing the number of layers of CFRP did not influence the capacity of the compression struts. Siddique and Damatty [6] numerically studied the enhancement in buckling capacity of steel plates repaired by GFRP plates. The retrofitted plate capacity was governed by the ultimate shear capacity of the adhesive, ultimate axial capacity of the GFRP, or instability of the system. The failure mode was found depending on the slenderness ratio of the plate and the thickness of the GFRP. Kaya et al. [3] investigated the effectiveness of a GFRP-based technique for rapid retrofit of buckled steel piles and columns. Thirteen short steel columns with different degrees of section loss which had previously failed by inelastic buckling were repaired with GRFP jackets filled with grout and tested under axial compression. The experimental results demonstrated that the concrete filled GFRP jacket repair system restored the axial capacity of buckled columns to between 69% and 104% of the capacity of the undamaged control column. The repair effectiveness varied with the severity of the flange and web thickness reductions.

While the use of externally-bonded FRP can be an effective means of repairing corroded steel piles, the approach presents several challenges: (1) Achieving adequate bond between the steel and the FRP is essential to the performance of the system, but challenging in terms of surface preparation and allowing adequate curing time, which is further complicated in underwater applications [10]. (2) Curing of composites takes time meaning that the repaired structure may need to be kept out of service for a period while the repair gains strength. This is also the case for concrete jacket type repairs which are also common. (3) Finally, the installation of FRP often requires specialized skills adding to the overall repair cost.

In this paper, the performance of a friction-type bolted steel plate-based repair system is evaluated experimentally and analytically. The proposed system can be installed rapidly using traditional construction skills, does not require curing time and therefore will be effective immediately after installation, and does not require any permanent modification of the existing structure, such as bolting or welding directly to the existing pile. The effectiveness of this approach is validated through large-scale tests. Rational guidelines for the design of this type of repair system are presented and a numerical study is conducted to evaluate the effect of key parameters on the performance of the system.

2. Design of the steel-based repair system

Studies indicated that the degree of flange deterioration was the most critical factor affecting the remaining axial capacity of a partially corroded steel H-piles [11–13]. This is because: (1) the flanges contribute more to the weak-axis moment of inertia of the section, and (2) causing the web to become slender requires a greater reduction of thickness compared to the flanges, since the web is a stiffened element while the flanges are unstiffened. Therefore, the repair system was designed primarily to reinforce the member by stabilizing the flanges. Strengthening the flanges delays flange local buckling while the strengthened flange contributes to the increment of the rotational fixity at the flange-to-web junction, which increases the plate buckling capacity of the web.

Fig. 2 illustrates the friction-type bolted steel plate-based repair system. The system consists of three plates that are clamped to each flange, one main steel plate and two clamping plates. The plates are coated with a high friction coating and mounted to the flanges as shown. Pretensioned structural steel bolts are used to clamp the plates to the flanges and to generate the normal force required to develop the appropriate level of friction at the interface. Axial load is transferred to the main plates of the repair system through friction over a load introduction length, L_d, on either end of the corroded region, L_c. The repair system contributes to the capacity of the pile in two ways. First, it provides an alternative load path for load to bridge across the corroded region in the pile thereby reducing the demand on the slender elements in the deteriorated region of the pile. Second, it supports the flanges thereby enhancing the flange local buckling capacity of the corroded section.

The required axial capacity obtained from the repair system, $P_{n,r}$, can be determined using Eq. (1)

$$P_{n,r} = P_{n,u} - P_{n,c}, \tag{1}$$

where, $P_{n,c}$ is the remaining axial capacity of corroded pile; $P_{n,u}$ is the target capacity of the repaired pile, which is taken as the nominal capacity of the un-damaged pile. The remaining axial capacity of a corroded pile, $P_{n,c}$, can be predicted by finite element analysis (FEA) which provides an accurate prediction of the capacity of H-piles with localized corrosion, but may also be conservatively calculated using the design equations in different design specifications [11–13]. The retrofitting target capacity, $P_{n,u}$ can be calculated according to the design approaches provided by AISC [14] and AASHTO [15] for the un-deteriorated member.

2.1. Determination of size, number, and spacing of bolts

Based on the required friction force, $P_{n,r}$, the size and number of bolts can be calculated according to the strength of a slip-critical connection specified in AASHTO [15]. The required number of bolts, $N_{b,d}$, over each development length, L_d, can be determined according to Eqs. (2) and (3),

$$N_{b,d} = P_{n,r} / R_n, \tag{2}$$