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軸方向荷重を受ける溶接添接補修された腐食劣化鋼管杭の性能評価

PERFORMANCE OF STEEL PIPE PILES REPAIRED BY PATCH WELDING CONSIDERING THE EXISTING AXIAL LOADS

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ABSTRACT Patch welding is a common method to repair corrosion-damaged steel structures. This paper investigates the performance of steel pipe piles repaired by patch welding considering the effect of the existing axial compressive loads. The performance of pipe piles is evaluated by a set of finite element (FE) analysis, and the mechanism of load transfer in the repaired pipe piles is examined. A minimum patch thickness to recover the initial stiffness and the strength of the corrosion-damaged pipe piles is proposed. Some practical issues in the welding repair design are also discussed.

Key words: 溶接補修, 荷重伝達, 有限要素解析, 鋼管杭
welding repair, load transfer, FE analysis, steel pipe pile

1. INTRODUCTION

The structural performance of offshore and port steel structures deteriorates rapidly once the corrosion protection such as painting degrades to a certain limit due to severe corrosive environment. Generally, it needs several repair works to extend the structural life to the designed service life. Typical deterioration curves of painting system and the corresponding structural performance are shown in Fig. 1 [1]. To achieve cost effective functionality and quality and to enable offshore and port structures to generate maximum direct and indirect income for minimal Whole Life Cost (WLC), Life Cycle Management (LCM) is regarded as an effective management approach [2, 3]. In order to implement LCM, structural performance during its life cycle should be understood beforehand.

Many researchers engage in understanding structural deterioration due to material loss and degradation, and many works have been done for countermeasures against corrosion and better design methods for repair [4-9]. It is necessary to investigate not only how a structure is deteriorating and how it should be repaired, but also how it would work after certain repair to fully grasp the structural performance over a life span. In addition, although extensive studies have examined the repair effect of corrosion-damaged structural members by various repair methods, most of them were conducted without applying any service loads on the specimens or components [10-13]. Actually, the existing service loads in the structural members vary and sometimes can be very large depending on their initial design loads, corrosion features, and the accidental load conditions, such as earthquake, tsunami, and vessel collision.

Particularly, in the area of welding repair of offshore and port steel structures, the research team of this paper has studied mechanical properties of underwater wet welds [14, 15], examined the repair effect of welding patch repair [16], and evaluated the current design of welding repair [17]. As a continuous work to supplement and complement the research, this paper further studies the performance of welding patch

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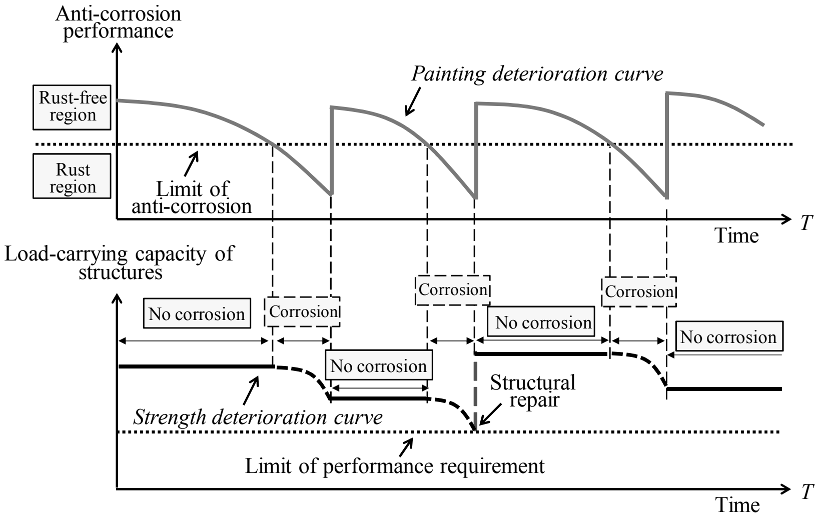


Fig. 1 Deterioration curves of painting system and structural performance [1]

repaired steel pipe piles with special attention paid to the effect of the existing axial compressive loads. The paper starts with a set of finite element (FE) analysis on welding repaired pipe piles under axial compression, and then presents an analytical study to clarify the mechanism of load transfer in the repaired pipe piles. By integrating research results, the paper ends with design proposals and some practical solutions for the repair design.

2. FINITE ELEMENT ANALYSIS

2.1 Finite Element (FE) Model

A general procedure of welding patch repair is schematically shown in Fig. 2 [16]. The cuts on the two patch plates form two patch slits, which are used to fillet weld patch plates to the base pipe pile, and two patch plates are further welded together by groove welding. One of the typical types of steel pipe pile used in offshore and port structures with an outer diameter of 500 mm and a wall thickness of 12 mm is used in the FE analysis. There are two reference piles, one is the

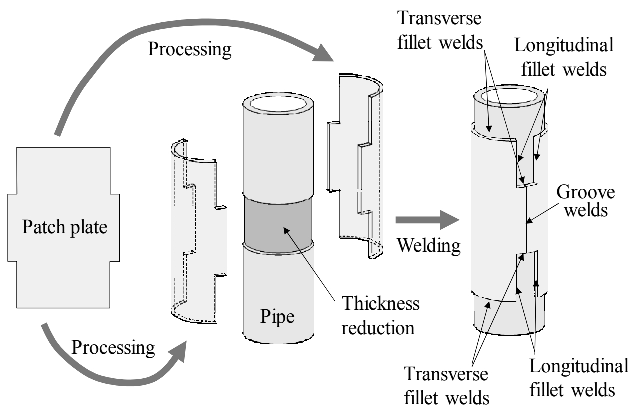


Fig. 2 A general procedure of welding patch repair [16]

intact pile, and the other is the thickness-reduced pile, where a uniform thickness reduction of 6 mm is introduced to represent corrosion damage in the middle portion of pipe piles with a length of 500 mm, which is long enough to accommodate one half-sine wave length of about 110 mm of the buckle in the following FE analysis.

Four repaired pipe piles using patch welding are also modeled according to the repair design method proposed by Chen et al. [17]. Patch plates used in the repair have a design thickness of 9 mm, which is a summation of the required thickness of 7 mm (6.6 mm is the calculated value to fully recover the stiffness of the corrosion-damaged pipe pile under axial compression) and the corrosion sacrificial thickness of 2 mm. Four repairs are different only in the existing load levels before repair, noted as the preload levels in this study, and they are $0.00P_{y0}$, representing a zero-preload level; $0.12P_{y0}$, representing a small preload level; $0.29P_{y0}$, representing a medium preload level; and $0.47P_{y0}$, representing a large preload level, where P_{y0} is the theoretical yielding load of the intact pipe pile as shown in Table 1. It is noted that $0.47P_{y0}$ is the preload level a little smaller than the one that could yield the damaged base steel before repair due to a half reduction in the wall thickness. Other structural parameters of pipe piles can be found in Table 1, where an effective length factor of 0.5 is used in the relevant calculations.

Because the slenderness ratio of pipe piles is 16.5, which is smaller than the critical slenderness ratio of 18 as specified in Ref. [18], the global buckling of pipe piles is not a concern and the compressive strength of

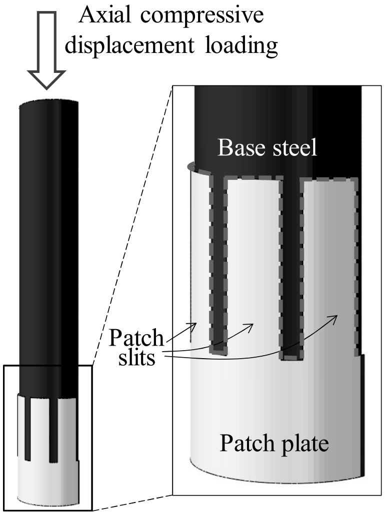


Fig. 3 A quarter of FE model

pipe piles σ_u is the same as the material yielding stress σ_{yb}. Due to the uniform thickness reduction in the damaged base steel and the symmetrical patch pattern, it is assumed that the local buckling of the damaged pile and four repaired piles has a symmetrical form about the central axis of pipe piles. In order to guide the intact pipe pile into the symmetric local buckling form, a small uniform thickness reduction of 0.01 mm in the base steel with the same length as that in the damaged pile is introduced in the FE model.

A quarter of FE model is constructed and analyzed in the general purpose FE analysis software ABAQUS [19] taking advantage of geometrical symmetry as shown in Fig. 3. After applying symmetrical boundary constrains to proper model boundaries, two reference piles, i.e., the intact pipe pile and the unrepaired pipe pile are applied with axial compressive displacement loading to their post buckling phase. The loading ends of the piles are constrained in such a way that only axial displacement is allowed. Four repaired piles are firstly applied with a designated preload level in compression with patch plates inactivated in the model, which represents the structural state before patch repair; after that, patch plates are activated in the model as a stress-free state, and then a compressive displacement loading is applied up to the post buckling phase of the repaired piles.

Material properties for base steel, STK400, and patch steel, SM400B, as shown in Table 2, are obtained from tensile coupon tests performed in Ref. [16] and material test curves are plotted in Fig. 4. Fillet welds are modeled by connector element CONN3D2, a three-dimensional, 2-node element, with a nonlinear applied load-relative displacement property in each translational component in the local Cartesian directions. Base pipe, patch plates and groove welds are modeled by shell element S4R. More modeling details can be found in Ref. [17].

Table 1 Structural parameters of pipe piles

Parameter	Notation	Value	Unit	Parameter	Notation	Value	Unit
Outer diameter	D	500	mm	Tested yielding stress of base steel	σ_{yb}	362	MPa
Intact thickness of base steel	t_b	12	mm	Cross-sectional area of the intact base steel	A_b	18,397	mm^2
Thickness reduction	Δt	6	mm	Cross-sectional area of the thickness reduced base steel	A_r	9,085	mm^2
Thickness of patch plate	t_p	9 (7)	mm	Cross-sectional area of patch steel	A_p	14,392 (11,150)	mm^2
Pipe length	l_0	5,600	mm	Theoretical yielding load of the intact pipe	P_{y0}	6,660	kN
Half length of the thickness-reduced portion	l_r	500	mm	Theoretical shortening of the intact pipe at P_{y0}	δ_{y0}	9.99	mm
Length of over-patch	l_{pl}	50	mm	Stiffness of intact pipe with $2l_r$'s length	K_{ro}	7,465	kN/mm
Slit width	l_{slit}	50	mm	Slenderness ratio of the intact pipe pile	λ	16.5	-
Length of each weld line	l_{wl0}	440 (390)	mm	Slenderness parameter of the intact pipe pile	$\bar{\lambda}$	0.215	-
Number of slits	n	8	-	Radius-thickness parameter of the intact pipe pile	R_t	0.060	-

Table 2 Mechanical properties of steels

Steel	Young's modulus E (GPa)	Poisson's ratio ν	Yielding stress σ_y (MPa)	Ultimate strength σ_u (MPa)	Elongation Δl (%)
STK400	203	0.28	362	394	41
SM400B	213	0.28	290	416	46

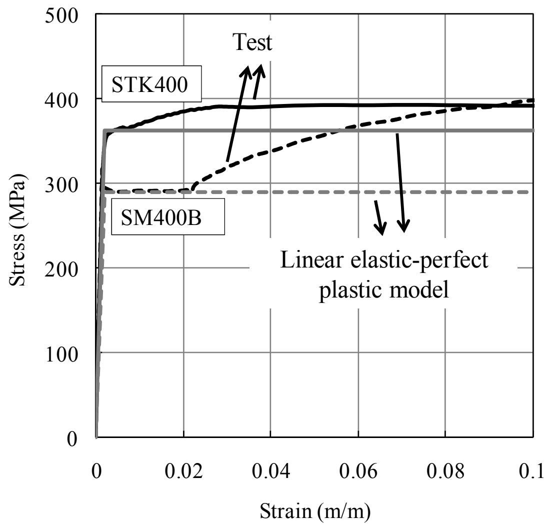


Fig. 4 Material constitutive curves

2.2 Results and Discussions

The compressive responses of six cases are plotted in Fig. 5 in terms of the normalized pipe shortening and the normalized applied load. It can be found that the intact pile shows a maximum load-carrying capacity, P_{max}, larger than the design strength P_{y0}, i.e., P_{max}/P_{y0} >1.0. The damaged pile without repair shows a great decrease in the load-carrying capacity as well as the deformation at its maximum load.

Four repaired piles with a patch thickness of 9 mm show similar response curves regardless of different preload levels. The strength of repaired piles is recovered to the design strength, and the deformation at their maximum loads is also considerably enhanced, although none of them reaches the deformation of the intact pile. The failure mode of four repaired piles is also examined through a contour plot of equivalent plastic strains, PEEQ, at $0.9P_{max}$ in the post peak phase. All repaired piles show the same failure mode in such a way that the local buckling occurs at the intact base steel adjacent to the repaired region as an example shown in Fig. 6(a).

The finding suggests that a patch repair can recover the strength of the damaged pipe pile to the design strength as long as the local buckling of the intact base steel dominates the failure mode, and once a patch repair design satisfies this condition, it is not necessary to further increase the patch thickness, because the strength of repaired piles is determined by the intact base steel rather than the patch repaired region.

Based on the aforementioned discussions, it seems that the examined design method is appropriate and effective to repair a damaged pipe pile, and different preloads appear to have no obvious effect on structural performance. However, as noted previously, the patch thickness of 9 mm used in the repaired piles is a design thickness taking into account of the sacrificial thickness of 2 mm, which means that the repaired piles are expected to provide satisfactory performance even with a patch thickness of 7 mm. To check whether this expectation can be met, a new FE model is analyzed under a preload level of $0.47P_{y0}$ without introducing the sacrificial thickness into patch plates, i.e., the thickness of patch plates is changed from 9 mm to 7 mm, and correspondingly, the length of each weld line is re-calculated to be 390 mm. The compressive response of the new model is also plotted in Fig. 4 for comparison.

It is found that the new repaired pile with a patch thickness of 7 mm fails to provide sufficient strength and to enhance the deformation at its maximum load. More importantly, the failure mode, as shown in Fig. 6(b), is the local buckling at the repaired region rather than the desired one at the intact base steel, suggesting that the patch thickness of 7 mm is not adequate in this repaired pile. It is therefore necessary to examine the minimum patch thickness required to recover the structural performance with presence of preloads, which will be discussed in the following section.

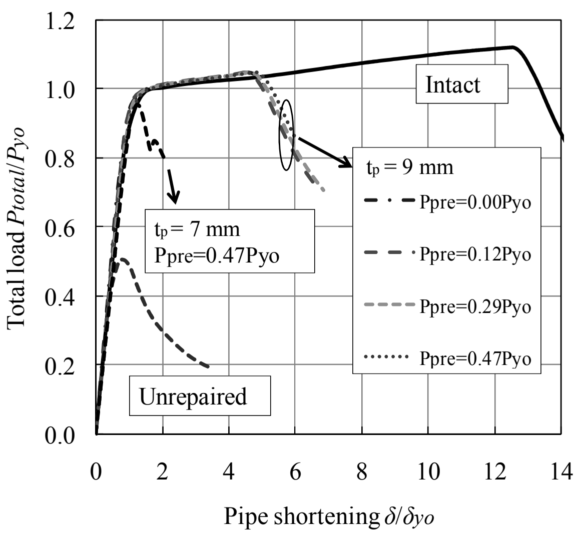
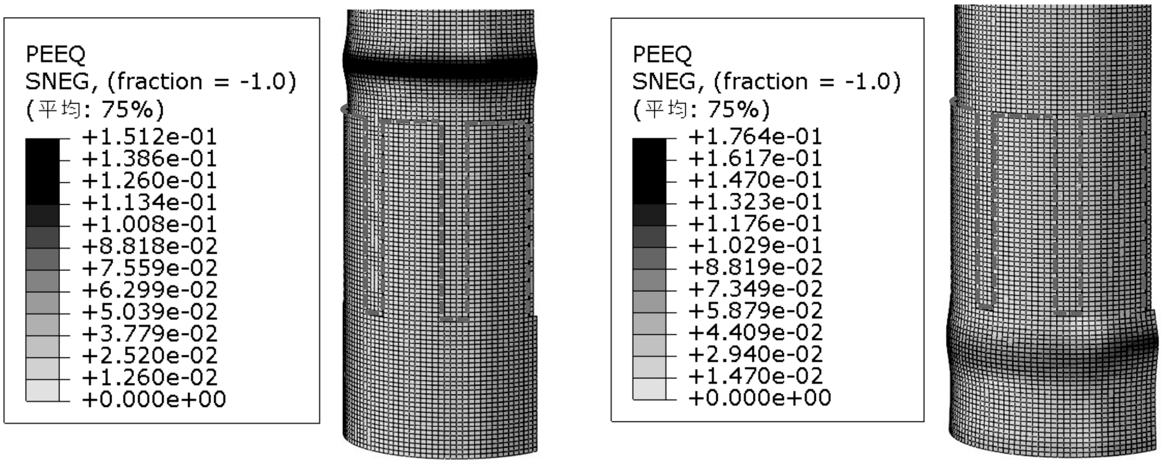


Fig. 5 Applied compressive load vs. pipe shortening



(a) P_{pre}/P_{y0}=0.47, t_p=9 mm (b) P_{pre}/P_{y0}=0.47, t_p=7 mm

Fig. 6 PEEQ contour plots at the post peak 0.9 P_{max}

3. MECHANISM OF LOAD TRANSFER

3.1 Incremental Load Share Ratio

Patch plates are welded to the preloaded pipe pile and join the damaged base steel to carry the additional loads coming into the pile. The load share ratio of patch plates is an essential parameter to understand the mechanism of load transfer in the repaired system. Because the material curve of STK400 steel obtained from the tensile coupon test as shown in Fig. 4 does not have an obvious yielding plateau. In order for the convenience of comparison between FE results and the following results from analytical derivation, the linear elastic-perfect plastic model is used to simplify material curves as shown in Fig. 4.

The FE analysis performed in section 2 is then re-analyzed by just simply substituting the material test curves with the model curves of two steels, and the results of load share ratios of the damaged base steel and patch plates of pipe piles at each load increment during the analysis, referred to as incremental load share ratios, are plotted in Fig. 7.

In the current Japanese repair design manual [20], the load share ratio of patch plates, which also equals to the incremental load share ratio of patch plates when all materials are in the elastic phase, can be calculated as $t_p/(t_r+t_p)$, where, t_p and t_r are the thickness of patch plates and the residual thickness of the damaged base steel, respectively. Therefore, this value is calculated to be 0.60 and 0.54, when t_p=9 mm, and 7 mm is used, respectively. And it is 0.58 and 0.52 correspondingly according to Eq. (1) proposed by Chen et al. [17] considering weld stiffness:

$$LSR = \frac{1}{1 + \dfrac{A_b A_r}{A_p} \cdot \dfrac{l_r + l_{p1} + A_p E / K_w}{A_b l_r + A_r l_{p1}}} \tag{1}$$

where, LSR is the load share ratio of patch plates; E is the Young's modulus of steel, which is assumed to be the same for base steel and patch steel; K_w is the total stiffness of fillet welds, which can be calculated according to Ref. [17]. Each cross-sectional area of repaired pipe piles can be calculated by $A_b=\pi(D-t_b)t_b$, $A_r=\pi(D-t_b-\Delta t)(t_b-\Delta t)$, and $A_p=\pi(D+t_p)t_p$. Eq. (1) is applicable when all materials are in the elastic phase.

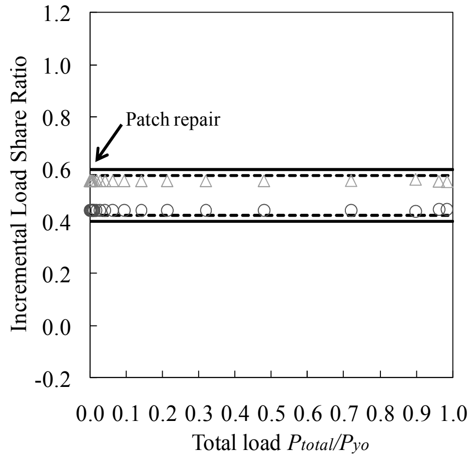
It is noted that the load share ratios calculated by the design manual and Chen et al. [17] do not consider the effect of preloads; therefore, they are constant values at different preload levels during the loading as shown in Fig. 7.

It is found in Fig. 7(a) that when there is no preload, the load share ratios of patch plates and the damaged base steel from two calculated methods and FE analysis show good agreement within the total load level of $P_{total}/P_{y0}\leq 1$. It is noteworthy that the load share ratios calculated from Chen et al. [17] do not show much difference from the design values, although they appear to be slightly closer to the results from FE analysis. This is reasonable because as also examined in Ref. [17], when a structural size factor ω, which is a non-dimensional parameter indicating the relative axial compressive stiffness of each portion in the repaired pile and the effect of weld stiffness on the calculation of LSR, as shown in Eq. (2) is larger than 20, the error by neglecting the effect of weld stiffness in the calculation of load share ratio of patch plates is within 4%, and for repaired pipe piles discussed in this study, the value of ω is 25, resulting in negligible difference in the calculation.

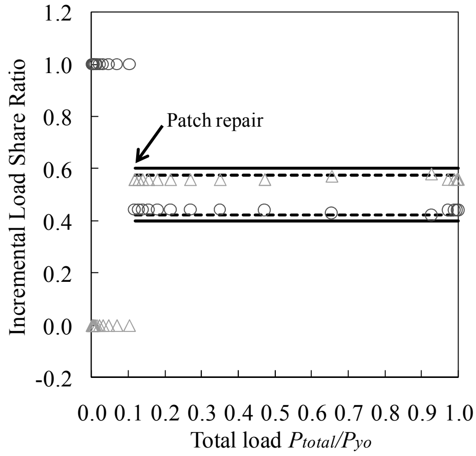
$$\omega = D\left(\frac{l_r}{A_r} + \frac{l_{p1}}{A_b} + \frac{l_r + l_{p1}}{A_p}\right) \qquad (2)$$

When patch repair is applied to the damaged pipe pile with a small preload level of $0.12P_{y0}$, the load share ratio of the damaged base steel decreases from 1 to about 0.42 once patch plates start to carry the loads as shown in Fig. 7(b). The load share ratios of patch plates and the damaged base steel after patch repair are the same as those found in the repaired pile without the preload as shown in Fig. 7(a).

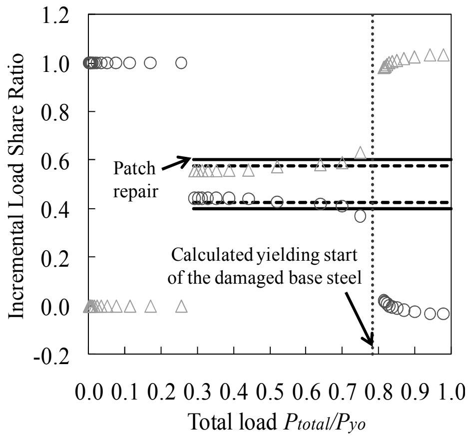
It is noted that despite of small difference among load share ratios calculated by three methods, i.e., design manual, Eq. (1), and FE analysis, a general trend



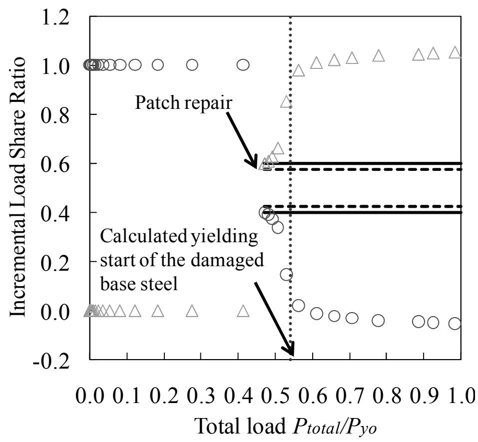
(a) P_{pre}/P_{y0}=0; t_p=9 mm



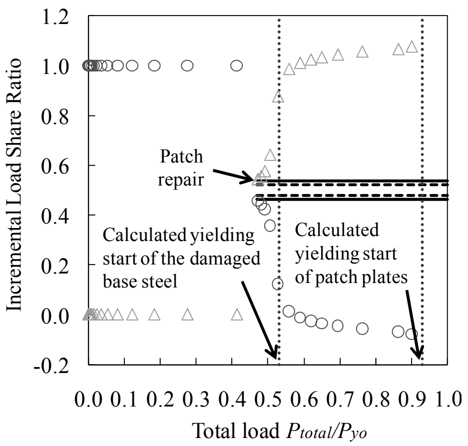
(b) P_{pre}/P_{y0}=0.12; t_p=9 mm



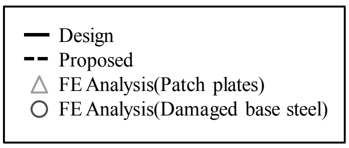
(c) P_{pre}/P_{y0}=0.29; t_p=9 mm



(d) P_{pre}/P_{y0}=0.47; t_p=9 mm



(e) P_{pre}/P_{y0}=0.47; t_p=7 mm



(f) Legend of figures

Fig. 7 Load share in the repaired piles

is found that LSR of patch plates calculated by the design manual is always slightly larger than that calculated by Eq. (1), which is reasonable as discussed earlier considering that Eq. (1) takes weld stiffness into account, resulting in a smaller LSR of patch plates. In addition, FE results show slightly smaller LSR values than ones calculated by Eq. (1) because the FE model further considers the deformation of patch slits, which is not considered when applying Eq. (1) to calculate the load share ratio of patch plates.

When a medium preload of $0.29P_{y0}$ is applied, a rapid increase (decrease) of load share ratio of patch plates (the damaged base steel) is observed in the FE analysis at a total load level P_{total}/P_{y0} close to 0.80 as shown in Fig. 7(c). By checking plastic strains in the FE model, it is found that the rapid change of load share ratios is caused by the yielding and the immediately following buckling of the damaged base steel. Thereafter, patch plates alone have to carry all additional loads imposed on the repaired pile and the loads released from the buckled damaged base pipe due to its post-peak response, which causes the incremental load share ratio of patch plates is larger than 1 and that of the damaged base pipe is smaller than 0 after the yielding of the damaged base pipe starts. A similar observation can be found in Fig. 7(d), where the preload level of $0.47P_{y0}$ is close to the yielding load of the damaged base steel before repair.

In four cases with t_p=9mm, the pile strength reaches the design strength of the intact pile, i.e., $P_{max}/P_{y0}>1$. However, when t_p=7mm is used in the repaired piles, the pile strength cannot reach the design strength, and the maximum strength is around $0.93P_{y0}$ as shown in Fig. 7(e), which is also the load level that yields patch steels by checking the FE model. This observation suggests that the strength of the repaired pile is determined by the strength of patch plates, and the patch thickness has to be increased in order to further improve the pile strength.

The findings implicate that a cost effective thickness of patch plates is the one with which patch plates yield just after the intact base steel yields. If the thickness is thinner, the pile strength cannot be recovered to the design strength. On the other hand, if it is thicker, not only the repair cost would be increased due to the thicker patch steel and consequently the longer weld lines, but also the pile strength cannot be further improved, because the failure mode that the yielding and the following buckling of the intact base steel would dominate the pile strength.

3.2 Yielding Loads of the Damaged Base Steel and Patch Plates

To determine the cost effective thickness of patch plates for repair, the yielding loads of the damaged base steel and patch plates, two important load levels during the loading history of repaired piles, are discussed following. Considering a repaired pile under axial compression, the following stress states exist:

$$\sigma_{bo} = \frac{P_{pre} + \Delta P}{A_b} \tag{3}$$

$$\sigma_{br} = \frac{P_{pre} + \Delta P_{br}}{A_r} \tag{4}$$

$$\sigma_p = \frac{\Delta P_p}{A_p} \tag{5}$$

where, σ_{bo}, σ_{br}, and σ_p are axial stresses in the intact base steel, the damaged base steel, and patch plates, respectively; P_{pre} is the preload applied to the damaged pile before patch repair; ΔP, ΔP_{br}, and ΔP_p are the summation of all additional loads imposed to the pipe piles, the additional loads carried by the damaged base steel and patch plates, respectively. And the relation between them exists:

$$\Delta P = \Delta P_{br} + \Delta P_p \tag{6}$$

When base steel and patch steel are both elastic, the following relations exist:

$$\Delta P_{br} = (1 - LSR) \cdot \Delta P \tag{7}$$

$$\Delta P_p = LSR \cdot \Delta P \tag{8}$$

With the increase of the additional compressive loads, the damaged base steel would yield on the condition σ_{br}=σ_{yb}. At this point, the normalized additional load and the total load applied to the repaired pile can be calculated respectively as:

$$\left(\frac{\Delta P}{P_{y0}}\right)_{ybr} = \frac{1}{1 - LSR} \cdot \left[\frac{A_r}{A_b} - \left(\frac{P_{pre}}{P_{y0}}\right)\right] \tag{9}$$

$$\left(\frac{P_{total}}{P_{y0}}\right)_{ybr} = \frac{1}{1 - LSR} \cdot \left[\frac{A_r}{A_b} - LSR \cdot \left(\frac{P_{pre}}{P_{y0}}\right)\right] \tag{10}$$

Eqs. (9) and (10) are useful when evaluating the yielding state of an existing patch repaired pile. Take the repaired piles presented in this study for example, the calculated yielding loads of the damaged base steel are indicated in Figs. 7(c), (d), and (e), and they show good agreement with the FE results; while they are not shown in Figs. 7(a) and (b) because the yielding loads of the damaged base steel in these two preload levels occur beyond the total load level of P_{total}/P_{y0}>1.

Moreover, a repaired design that prevents yielding of the damaged base steel can be guaranteed if the following condition is satisfied:

$$\left(\frac{P_{total}}{P_{y0}}\right)_{ybr} > 1 \tag{11}$$

which can be rearranged considering Eq. (10):

$$LSR > \frac{A_b - A_r}{A_b} \cdot \frac{1}{1-\left(\frac{P_{pre}}{P_{y0}}\right)} \cong \frac{\Delta t}{t_b} \cdot \frac{1}{1-\left(\frac{P_{pre}}{P_{y0}}\right)} \tag{12}$$

However, it should be noted that the repair design according to Eq. (12) is not cost effective because the residual strength of the damaged base steel is not fully utilized in the repaired system and when the preload level is large, take P_{pre}/P_{y0} close to $(t_b\text{-}\Delta t)/t_b$ for example, the load share ratio of patch plates has to be close to 1 in order to avoid the forthcoming yielding of the damaged base steel, which would result in very thick patch plates in the repair.

Therefore, it is necessary to consider a further loading after the yielding of the damaged base steel up to the yielding of patch plates. At the yielding of patch plates, the normalized load carried by patch plates can be calculated by:

$$\left(\frac{P_p}{P_{y0}}\right)_{yp} = LSR \cdot \left[\left(\frac{P_{total}}{P_{y0}}\right)_{ybr} - \left(\frac{P_{pre}}{P_{y0}}\right)\right] + 1 \cdot \left[\left(\frac{P_{total}}{P_{y0}}\right)_{yp} - \left(\frac{P_{total}}{P_{y0}}\right)_{ybr}\right] \tag{13}$$

where, $(P_p/P_{y0})_{yp}$ and $(P_{total}/P_{y0})_{yp}$ are the normalized loads in patch plates and the normalized total load in the repaired pile at the yielding of patch plates, respectively, and the latter can be calculated by:

$$\left(\frac{P_{total}}{P_{y0}}\right)_{yp} = \frac{A_r}{A_b} + \frac{A_p}{A_b} \cdot \frac{\sigma_{yp}}{\sigma_{yb}} \tag{14}$$

where, σ_{yp} is the yielding stress of patch steel. For the repair piles discussed in this study, $(P_{total}/P_{y0})_{yp}$ is calculated to be 1.06 and 0.93 for the analyzed cases with t_p=9 and 7 mm, respectively. The value of 0.93 is indicated in Fig. 7 (e) and it shows good agreement with that observed in the FE analysis, while the value of 1.06 is not indicated in Fig. 7 (a) to (d) because the load level larger than the design strength is beyond the concern of discussion.

As the repair concept addressed previously, a patch repair is cost effective when the yielding of patch plates occurs just after the yielding of the intact base steel, therefore, the following condition should be satisfied:

$$\left(\frac{P_{total}}{P_{y0}}\right)_{yp} > 1 \tag{15}$$

Consequently, the required thickness of patch plates, t_p, can be calculated considering Eqs. (14) and (15) together:

$$t_p > \sqrt{\frac{1}{4}D^2 + H} - \frac{1}{2}D \tag{16}$$

where,

$$H = (D \cdot \Delta t - \Delta t^2)\frac{\sigma_{yb}}{\sigma_{yp}} \tag{17}$$

Considering the minimum diameter of steel pipe piles specified in JIS A5525 is larger than 300 mm, Eq. (16) can be further simplified to a slightly conservative calculation:

$$t_p > \frac{\sigma_{yb}}{\sigma_{yp}} \cdot \Delta t \tag{18}$$

It is of interest to note that unlike the patch thickness requirement, or the *LSR* requirement, to avoid the yielding of the damaged base steel from Eq. (12), the required patch thickness calculated by Eq. (18) is not relevant to preload levels. This means that as long as patch plates are thick enough to remain elastic until the yielding of the intact base steel, the preload level does not affect the required pile to reach the design strength. This finding is reasonable considering that the damaged base steel and the intact base steel carry the same amount of preload before patch repair. If the preload level is larger, the damaged base steel would yield earlier, resulting in patch plates to carry all additional loads earlier, the intact base steel would also yield earlier, vice versa.

It is also important to note that t_p calculated by Eq. (18) satisfies the strength requirement of patch plates for the repaired piles. However, when the yielding stress of patch steel is larger than that of base steel, it does not mean that a patch thickness smaller than Δt can be used. This is because as an efficient repair, not only the strength should be recovered, but also the stiffness of the repaired portion. Chen et al. [17] has studied a minimum patch thickness, which is larger than Δt and can be calculated by t_p' as shown in Eq. (19), to fully recover the initial stiffness of the damaged pipe piles when there is no preload.

$$t_p' = \frac{1}{\pi D} \cdot \frac{(l_\mathrm{r} + l_\mathrm{p1}) A_\mathrm{b}}{\dfrac{A_\mathrm{b} l_\mathrm{r} + A_\mathrm{r} l_\mathrm{p1}}{A_\mathrm{b} - A_\mathrm{r}} - \dfrac{E}{K_\mathrm{w}} \cdot A_\mathrm{b}} \tag{19}$$

The calculation is still applicable to the cases with preloads when the initial stiffness is in the concern, because base steel and patch steel remain in the elastic phase right after the patch repair. At this point, the load share ratios of patch plates and the damaged base steel, which determine the initial stiffness of the repaired portion, show good agreement among the results from Chen et al., design, and FE analysis as shown in Fig. 7.

3.3 Two Special Preload Levels

Two special preload levels are discussed in this section, one is the zero-preload level, and the other is the maximum preload level, which yields the damaged base steel before patch repair and equals to $P_{pre}/P_{y0}=(t_b-\Delta t)/t_b$. For the former load level, it has been discussed and a minimum patch thickness t_p' should be used. It should be noted that Eq. (18) is not applicable to the pipe piles without preload, because once t_p' is used to recover the initial stiffness, the strength can be simultaneously recovered when this is no preload. And in this case, the yielding of the damaged base steel would not occur before the yielding of the intact base steel, which does not satisfy the premise to use Eq. (18), which requires the yielding of the damaged base steel to occur within the total load level of $P_{total}/P_{y0}\leq 1$.

For the preload level which yields the damaged base steel before patch repair, a patch thickness $t_p=t_b$ should be used to recover the initial stiffness of the repaired portion, because the damaged base steel cannot provide any stiffness due to material yielding. Meanwhile, the patch thickness should also satisfy Eq. (18) to recover the pile strength.

By integrating the findings presented, the minimum thickness of patch plates can be determined, as shown in Table 3, to guarantee an efficient repair of pipe piles under axial compression considering the different preload levels. In order to use the proposed patch thickness in the practical repair design, there are some issues to be clarified, which will be discussed in the next section.

4. SOME PRACTICAL ISSUES

4.1 Corrosion Features

For offshore and port steel structures, corrosion features, including the average residual wall thickness, thickness variation and distribution, surface roughness, local pits, etc. are too complex to be generalized as mathematical models with common acceptance, although the corroded specimens cut from fields have been delicately measured and tested [5, 13, 21]. It is essential to capture the corrosion features as precise as possible when predicting the residual strength of steel members, especially when they are under compression, where the local buckling dominates the failure mode of steel members.

However, the demand of precise survey of corrosion features is not as that crucial when the strength after repair, instead of the residual strength of pipe piles, is in the concern. This is because the failure mode of the repaired pipe piles due to local buckling is expected to

Table 3 Minimum patch thickness and the repaired performance

Preload level P_{pre}/P_{y0}	Minimum patch thickness t_{pmin}	Repaired performance		
		Initial stiffness K_r/K_{r0}*	Ultimate strength P_{max}/P_{y0}	Failure mode
0	t_p'	≥1	≥1	Yielding and buckling in the intact base steel
>0; <$(t_b-\Delta t)/t_b$	max(t_p'; $\sigma_{yb}/\sigma_{yp}\cdot\Delta t$)	≥1	≥1	
$(t_b-\Delta t)/t_b$	max(t_b ; $\sigma_{yb}/\sigma_{yp}\cdot\Delta t$)	≥1	≥1	

*Note: K_r is the initial axial stiffness of the repaired portion under compression; K_{r0} is defined in Table 1.

occur in the intact base steel, which is the portion far beyond the corrosion-damaged base steel. In this sense, the corrosion features except the minimum and the average residual wall thickness of the damaged base steel have little effect on the pile strength after repair.

Therefore, in the FE analysis presented in this study, an ideal uniform thickness reduction is employed to represent corrosion damage in pipe piles, and this treatment is not only for the convenience in modeling, but also because it would not generate much difference in the results when evaluating the performance of the repaired pipe piles.

4.2 Determination of Preloads

Generally, it is difficult or sometimes even impossible to accurately predict the existing loads, or preloads, in a corroded structural member even when the design load in the as-built state and its current corrosion features are both known. This is because pipe piles rarely work independently with each other; instead, they are usually assembled as a pile group to support the superstructure as an example shown in Fig. 8. This means that the pile group is a structurally redundant system and the existing load in one pile is determined not only by the conditions of its own, but also by those of the others.

Fortunately, a constant patch thickness t_{pmin}=max(t_p' ; $\sigma_{yb}/\sigma_{yp}\cdot\Delta t$) can be applied to a wide range of preload levels as long as the preload level is not at the two special cases as discussed in section 3.3. The zero-preload level is a rare load state existing in the actual structures and the use of t_{pmin}=max(t_p' ; $\sigma_{yb}/\sigma_{yp}\cdot\Delta t$) would simply give a conservative repair design. The preload level, at which the damaged base steel has already yielded before repair, exists when the corrosion damage is severe and the loss of steel is large. Although

Fig. 8 A group of pipe piles supporting a wharf

this preload level is difficult to determine quantitatively, the repair design manual provides some rules of thumb to judge the severity of corrosion when the residual strength of steel is not expected, implicating the yielding of the damaged steel before repair.

For example, it is specified in the manual that when the residual thickness of steel is less than 5 mm, the residual strength of steel is not expected [20, 22]; and the another use of the rules of thumb is stated in the design example in the manual that when pit corrosion is observed in a steel pipe pile all along the circumferential direction, the residual strength is not expected neither [22]. By using these empirical rules, the preload level can be estimated and further repair design is then possible.

4.3 Sacrificial Thickness t_{ps}

Without full understanding of the load transfer mechanism in the repaired piles, the sacrificial thickness t_{ps}, which is 2 mm used in the manual, sometimes provides indispensible stiffness and strength to the repaired piles, and this is actually beyond its intended purpose purely for corrosion sacrifice. In addition, it may be expected by some designers that the use of t_{ps} would give a conservative and safe repair design; however, it is not always the case by studying the load transfer in the repaired piles. Take this study for example, a patch thickness of 9 mm is too conservative when there is no preload, where only 7 mm is enough to satisfy the repaired performance; while the thickness of 9 mm is not adequate when the preload level is P_{pre}/P_{y0}=(t_b-Δt)/t_b, where a patch thickness of 12 mm is necessary.

After clarifying the mechanism of load transfer in the repaired piles, the use of t_{ps} can be reduced or even abandoned, and some other measures, such as FRP covering, taping, epoxy coating, etc., can be employed to provide corrosion proof for the patch-repaired pipe piles. Consequently, the repair cost may be reduced due to thinner patch plates and shorter weld lines without adversely affecting the structural performance.

5. CONCLUSIONS

This paper examined the performance of steel pipe piles repaired by patch welding considering the effect of the existing axial compressive loads. The mechanism of load transfer in the repaired piles is investigated. Main conclusions of this study can be drawn as:

(1) When there are existing axial loads applied to the corrosion-damaged pipe piles, a patch thickness required to recover the design strength of piles to their intact state can be calculated as $\sigma_{yb}/\sigma_{yp}\cdot\Delta t$, where σ_{yb}, σ_{yp}, and Δt are the yielding stresses of base steel and patch steel, and the thickness reduction in the damaged base steel, respectively.

(2) The load share ratio of patch plates calculated using the method proposed by Chen et al. as shown in Eq. (1) is proved to be more accurate than the design equation when both base steel and patch steel are in the elastic phase.

(3) The minimum patch thickness to fully recover both the initial stiffness and the design strength of the damaged pipe piles under compression is proposed in Table 3. The failure mode of the repaired pipe piles is expected to be the yielding and the following buckling of the intact base steel at the repaired piles.

It is noteworthy that residual stresses due to welding are not modeled in the FE analysis, neither considered in the analytical study in this paper. This is because the distribution and the magnitude of residual stresses generated in welding process are difficult to characterize, especially when there are many weld lines and different preloads in the repaired pipe piles as the cases presented in this study. The effect of residual stresses due to welding on the repaired performance of pipe piles remains as future study.

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REFERENCES

[1] Fujii, K., Hashimoto, K., Watanabe, E., Itoh, Y., Sugiura, K., Nogami, I., Nagata, K., and Nakamura, H., A prediction method of strength deterioration in aging of circular steel tube corroded in marine environment., Doboku Gakkai Ronbunshuu A, JSCE, Vol. 66(1). pp. 92-105, 2010 (in Japanese).

[2] PIANC WG103, Life cycle management of port structures-recommended practice for implementation, International Navigation Association, PIANC report 103, pp. 1-56, 2008.

[3] Kazuaki, Z., Corrosion and life cycle management of port structures, Corrosion Science, Vol. 47, pp. 2353-2360, 2005.

[4] Watanabe, N. and Itoh, Y., Evaluation of surface roughness of a corroded steel angle exposed in oceanic environment for 19.5 years, Journal of Structural Engineering, JSCE, Vol. 54A. pp. 492-503, 2008.

[5] Yamasawa, T., Nogami, K., Itoh, Y., Watanabe, E., Sugiura, K., Fujii, K., and Nagata, K., Corrosion shapes of steel angle member under oceanic exposure during 19.5 years, Doboku Gakkai Ronbunshuu A, JSCE, Vol. 64(1). pp. 27-37, 2008 (in Japanese).

[6] Itoh, Y., Tsubouchi, S., and Kim, I. T., Corrosion deterioration characteristics of various repainted steels considering accelerated exposure test results, Doboku Gakkai Ronbunshuu A, JSCE, Vol. 64(3). pp. 556-570, 2008 (in Japanese).

[7] Itoh, Y., Shimizu, Y., and Koyama, A., Durability of steel bridge metallic coating systems for combined cyclic corrosion tests with salt water spray and acid rain spray, Doboku Gakkai Ronbunshuu A, JSCE, Vol. 63(4). pp. 795-810, 2007 (in Japanese).

[8] Kainuma, S., Hosomi, N., Goto, A., and Itoh, Y., Fundamental study on evaluation for time-dependent corrosion behavior of long steel members in marine environment, Doboku Gakkai Ronbunshuu A, JSCE, Vol. 65(2). pp. 440-453, 2009 (in Japanese).

[9] Sugiura, K., Tamura, I., Watanabe, E., Itoh, Y., Fujii, K., Nogami, K., and Nagata, K., Simplified evaluation of compressive strength of corroded steel plates, Doboku Gakkai Ronbunshuu A, JSCE, Vol. 63(1). pp. 43-55, 2007 (in Japanese).

[10] Fujii, K., Nakamura, H., Kondo, T., Hashimoto, K., Okimoto, H., and Nakamura, T., Experiments on bending buckling strength of corroded cylindrical shells, Journal of Structural Engineering, JSCE, Vol. 53A. pp. 784-793, 2007 (in Japanese).

[11] Yamasawa, T., Nogami, K., Sonobe, Y., and Katakura, K., Experimental study of steel column member on severe corroding environment, Journal

of Structural Engineering, JSCE, Vol. 55A. pp. 52-60, 2009 (in Japanese).

[12] Nara, S., Inoue, N., Matsunaga, K., and Takeuchi, S., Evaluation of ultimate compressive strength of corroded stiffened steel plates, Journal of Structural Engineering, JSCE, Vol. 55A. pp. 61-67, 2009 (in Japanese).

[13] Morishita, T., Fujii, K., Morita, K., Horii, H., and Nakamura, H., On rehabilitation of corroded steel plates by adhesive and steel cover plates, Journal of Structural Engineering, JSCE, Vol. 57A. pp. 747-755, 2011 (in Japanese).

[14] Watanabe, N., Kitane, Y., and Itoh, Y., Modeling of joint behavior of steel pipes repaired with steel plate by underwater wet welding, Journal of Structural Engineering, JSCE, Vol. 55A, pp. 903-914, 2009 (in Japanese).

[15] Chen, X., Kitane, Y., and Itoh, Y., Mechanical properties of fillet weld joints by underwater wet welding in repairing corrosion-damaged offshore steel structures, Journal of Structural Engineering, JSCE, Vol. 56A. pp. 742-755, 2010.

[16] Kitane, Y., Itoh, Y., Watanabe, N., and Matsuoka, K., Compressive and flexural tests of thickness-reduced steel pipes repaired with patch plates using underwater wet welding, Journal of Structural Engineering, JSCE, Vol. 55A, pp. 889-902, 2009 (in Japanese).

[17] Chen, X., Kitane, Y., and Itoh, Y., Evaluation of repair design on corrosion-damaged steel pipe piles using welded patch plates under compression, Journal of Structural Engineering, JSCE, Vol. 57A. pp. 756-768, 2011.

[18] The Japan Port & Harbour Association, Technical Specifications and Explanations on Port and Harbor Infrastructures, The Japan Port & Harbour Association, Japan, 2007 (in Japanese).

[19] Dassault Systèmes Simulia Corp., ABAQUS/Standard user’s manual, version 6.8, 2008.

[20] Coastal Development Institute of Technology, Port Steel Structure Corrosion-Prevention and Repair Manual (version 2009), Coastal Development Institute of Technology, Japan, 2009 (in Japanese).

[21] Appuhamy, J.M.R.S., Kaita, T., and Fujii, K., Prediction of residual strength of corroded tensile steel plates, International Journal of Steel Structures, Vol. 11(1), pp. 65-79, 2011.

[22] Coastal Development Institute of Technology, Port Steel Structure Corrosion-Prevention and Repair Manual (version 1997), Coastal Development Institute of Technology, Japan, 1997 (in Japanese).

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