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EVALUATION OF STRENGTH RECOVERY OF REPAIRED STEEL PIPE PILES

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ABSTRACT : Many coastal and offshore steel structures are in need of repair or strengthening due to corrosion problems. The use of steel patch plates welded underwater over corrosion-damaged areas is one of the most common repair procedures for corroded submerged steel pipe and sheet piles. A patch plate thickness, a required weld length, a size of a patch plate, etc. are the design parameters of the repair design. To determine these design parameters efficiently and achieve an effective repair design, strength of a repaired structural member has to be accurately evaluated. This paper summarizes an experimental study of steel pipes repaired with welded patch plates to evaluate the strength recovery resulting from repair. In this study, the thickness of a portion of steel pipes was reduced by half to simulate a reduction of the cross section from corrosion, and steel patch plates were fillet-welded to the pipes with a reduced thickness area. One set of specimens were welded in the open air, and the other welded in the underwater wet environment to understand effects of welding environments on strength of repaired pipes. The repaired pipes were tested in flexure or compression until failure. Based on the experimental results, stiffness and strength recoveries were evaluated, and the effectiveness of patch plates was also examined.

KEYWORDS: Repair, Steel pipe pile, Underwater wet welding, Strength recovery, Corrosion

1. INTRODUCTION

There are a significant number of marine steel structures suffering severe corrosion damage, and they are seriously in need of repair or strengthening to prevent structural failure. One of the most common repair procedures for corrosion-damaged submerged structural steel components is the welding of steel patch plates over the corrosion-damaged areas in the underwater wet environment [1,2].

Underwater welding is not a very new technique. It is becoming a more and more recognized and important technique in recent years, especially in the oil and gas industry to maintain submerged steel structures for energy explorations [3,4,5]. Underwater welding can be classified into two categories: dry welding and wet welding [3,6]. In the underwater dry welding, a dry environment is established around the welding area by constructing a dry chamber, and the welding is performed in the chamber. On the other hand, in the underwater wet welding, the area to be welded is directly exposed to water, and the welding is performed by a diver in a wet environment. Since the underwater wet welding does not require construction of a chamber and any heavy equipments, it is much more efficient and economical welding than the dry welding. Wet welding repairs can be completed at a significantly lower cost than the dry welding repairs [5]. In addition, in the wet welding, the welder can reach portions of structures where it may be difficult to construct a dry chamber.

However, there are a few disadvantages of the wet welding. First of all, the welder has to weld under the influence of ocean currents and a low visibility condition. Secondly, the weld metal undergoes a rapid cooling since it is directly exposed to the surrounding water. The quenching increases tensile

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strength of the weld, but it increases hardness and decreases ductility and impact strength. Thirdly, hydrogen deassociated from water dissolves into the weld metal and heat affected zones. The high hydrogen content in the weld metal can result in embrittlement of the material and microscopic cracks [7,8]. Lastly, the inspection of welds deposited in the underwater wet environment is much more difficult than that of those deposited in the open air. These factors can change the mechanical behavior of welded connections made by the wet welding and may lower the welding quality [9,10].

Although there have been some studies [11] on the load carrying capacity of corrosion-damaged steel pipes, the load carrying capacity of corrosion-damaged pipes repaired in the underwater wet environment is not well understood. Therefore, an experimental study was performed to examine strength recovery of steel pipes repaired with patch plates welded in the wet environment. One set of test specimens were welded in the open air, and the other welded in the wet environment to understand effects of welding environments on strength of repaired pipes. The repaired pipes were tested in flexure or compression until failure. Based on the experimental results, stiffness and strength recoveries were evaluated, and the effectiveness of patch plates was also examined.

2. EXPERIMENTAL PROGRAM

2.1 TEST SPECIMENS AND REPAIR DESIGN

Steel pipes with an outer diameter of 216.3 mm and a thickness of 12.7 mm, specified as STK400 in Japanese Industrial Standard (JIS) G3444 were used in this study. The radius to wall-thickness ratio is 8.02. To simulate a thickness reduction due to corrosion, the pipe thickness was reduced by 6 mm uniformly in the circumferential direction over a length of 150 mm.

The repair method used in this study is depicted in Figure 1. A thickness of a patch plate and lengths of welds were determined so as to restore strength of a repaired pipe to the same level as that of an intact pipe, where the allowable stress design method was used, and allowable stresses used are shown in Table 1. The specified fillet weld size was 6 mm. Only side fillet welds were considered in the design. Five different types of specimens were designed in this study. Type 0 is a new pipe. Type 1 has a 150-mm long reduced thickness section. Type 2, Type 3, and Type 4 all have a 150-mm long reduced thickness section, and patch plates are welded to cover the reduced thickness portion as repair. Type 2 has 6-mm thick patch plates welded over the reduced thickness portion, and a length of side fillet welds are about 1/4 of a required length in the design. Type 3 also has 6-mm thick patch plates; however, a required length of side fillet welds is provided. Type 4 has twice as many as the number of side fillet welds than that of Type 2 or Type 3, and it has 12-mm thick patch plates. Test specimens are summarized in Table 2. Chemical compositions of steels used in this study are shown in Table 3, where yield and tensile strengths obtained from steel tensile coupon tests are also listed.

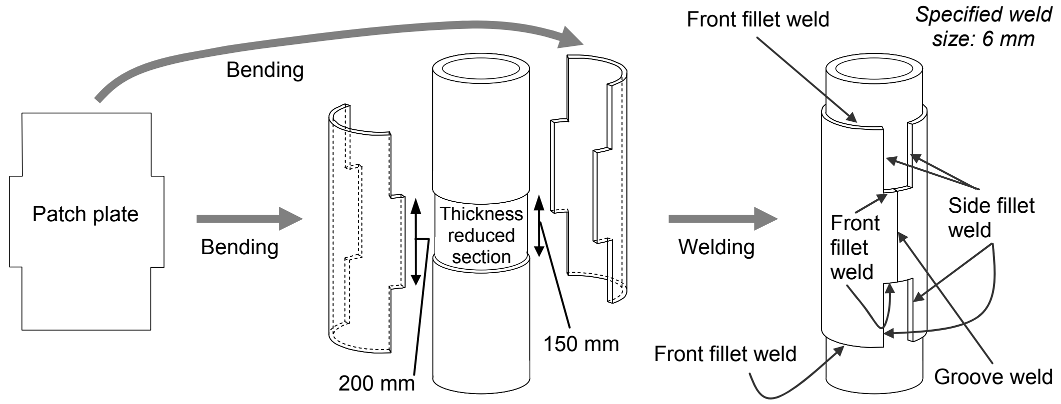


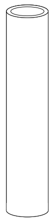
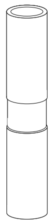
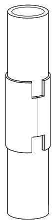
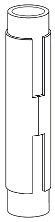
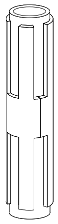
Figure 1. Repair Method by Welded Patch Plates

One set of specimens were welded in the open air, and the other set were in the underwater wet environment so that differences in the load-carrying capacity resulting from the welding environment could be examined. The underwater wet welding was carried out in the pool filled with natural seawater. The pool was continuously supplied with new seawater from the sea, and the temperature was 26˚C when the welding was carried out.

Table 1. Allowable Stress (MPa) [1]

	STK400 (pipe)	SM400B (patch)	Field weld
Axial tension/compression	137	137	--
Flexural tension/compression	137	137	--
Shear	78.5	78.5	62.7

Table 2. Test Specimens

	Type 0		Type 1		Type 2		Type 3		Type 4	
Specimen type										
Thickness reduction (mm)	0		6		6		6		6	
Repair	No		No		Yes		Yes		Yes	
Thickness of patch (mm)	--		--		6		6		12	
Loading*	C	B	C	B	C	B	C	B	C	B
Length of each side fillet weld (mm)	--		--		140	80	--	300	380	370
# of side fillet welds**	--		--		4		4		8	
Specimen designation***	KN0C	KN0B	KN1C	KN1B	KA2C KW2C	KA2B KW2B	--	KA3B KW3B	KA4C KW4C	KA4B KW4B

* C: compression, B: four-point bending

** Number of fillet welds for the half patch plate

*** The second letter of the specimen designation shows a welding environment:
N: no weld, A: open air welding, W: underwater wet welding

Table 3. Chemical Composition and Strength of Steels

Material	JIS designation	Chemical composition (%)					Yield stress (MPa)	Tensile strength (MPa)
		C	Si	Mn	P	S		
Pipe	STK400	0.12	0.10	0.56	0.013	0.006	362	394
Patch (t=6 mm)	SM400B	0.11	0.18	0.99	0.022	0.005	269	406
Patch (t=12 mm)	SM400B	0.15	0.15	0.71	0.013	0.006	271	391
Electrode* (d=4 mm)	D4301	0.10	0.10	0.43	0.015	0.007	410	460

* Data of electrode are from a product catalog.

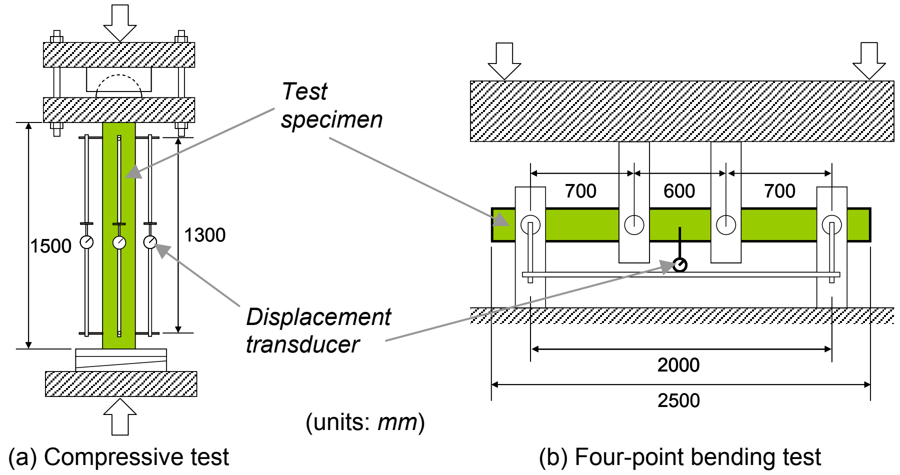


Figure 2. Test Setups

2.2 TEST SETUP

Figure 2 shows test setups for compressive and four-point bending tests. Compressive test specimens were 1,500 mm long, and shortening was measured for a 1,300 mm long portion of a specimen. The distance between the two supports of the four-point bending test was 2,000 mm, and the two loading points were 600 mm apart. A flexural specimen was fixed to the axle supported by axle bearings, and rotation was allowed to rotate at the supports and loading points. The load was applied monotonically to failure.

3. RESULTS AND DISCUSSIONS

3.1 COMPRESSIVE TEST

Figure 3 shows load-shortening curves from the compressive tests. Both load and shortening in Figure 3 were normalized by the theoretical yield load, P_{y0}, and the theoretical yield shortening, δ_{y0}, of Type 0 specimen (KN0C), respectively. Table 4 summarizes the initial stiffness, K_I, the obtained maximum load, P_{max}, and the shortening at the maximum load, δ_{max}, for each specimen. The initial stiffness was determined from the load-shortening curve up to 60% of the theoretical yield load.

Failure modes of Type 0 and Type 4 were the same, and they were plastic local buckling near the ends of specimen. Type 4 did not show any local buckling or weld failure in the repaired region. Type 1 showed plastic local buckling in the reduced thickness portion. Type 2 showed plastic local buckling of the repaired portion, resulting in failure of front and side fillet welds.

Table 4 shows that the initial stiffnesses from the tests are in good agreement with theoretical values, where the maximum relative difference is only 3%.

The ultimate strengths of Type 4 specimens were close to that of Type 0 because their failure modes were similar. For Type 2 specimens, the ultimate strengths were about 10% smaller than that of Type 0, and δ_{max} values were about 1/3 of that of Type 0.

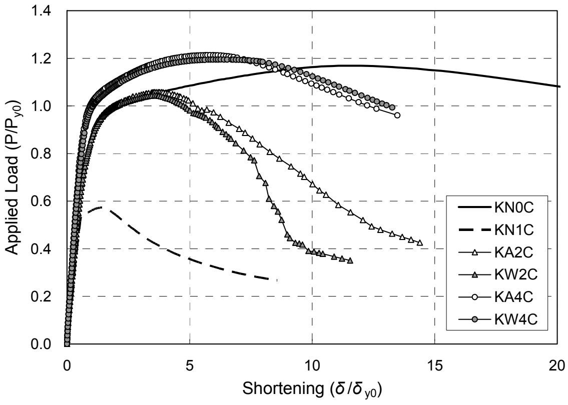


Figure 3. Load-Shortening Curves (Compressive test)

Table 4. Stiffness, Ultimate Strength, and Shortening at Ultimate Strength (Compressive test)

Specimen	Type 0	Type 1	Type 2		Type 4	
	KN0C	KN1C	KA2C (Air)	KW2C (Wet)	KA4C (Air)	KW4C (Wet)
K_I (MN/mm) (% *error* from theory)	1.23 (*+1.0*)	1.09 (*-0.78*)	1.37 (*+1.5*)	1.35 (*+1.2*)	1.83 (*-0.54*)	1.79 (*-3.4*)
P_{max} (MN)	3.29	1.61	2.98	2.94	3.42	3.36
δ_{max} (mm)	26.1	3.11	8.61	8.25	13.1	14.5
P_{max}/P_{y0}	1.17	0.57	1.06	1.04	1.21	1.20
δ_{max}/δ_{y0}	11.3	1.34	3.72	3.56	5.65	6.27

There was not much difference in the ultimate strength or shortening at the ultimate strength between specimens welded in the open air and those in the underwater wet environment.

3.2 FOUR-POINT BENDING TEST

Figure 4 shows load-deflection curves from the four-point bending tests. Deflection was measured at midspan. Both load and deflection in Figure 4 were normalized by the theoretical yield load, P_{y0}, and the theoretical yield deflection, δ_{y0}, of Type 0 specimen (KN0B), respectively. Table 5 summarizes the initial stiffness, K_I, the maximum load, P_{max}, and the deflection at the maximum load, δ_{max}, for each specimen.

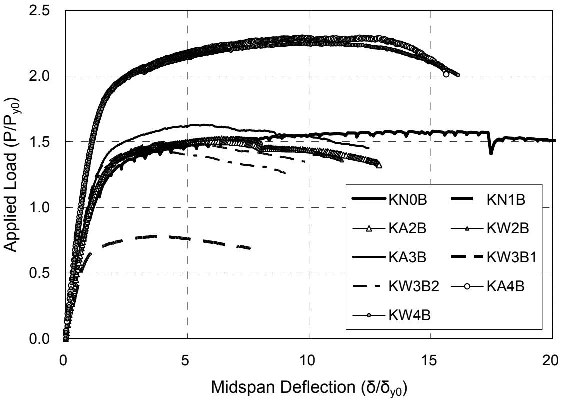


Figure 4. Load-Deflection Curves (Four-point bending test)

All specimens formed a plastic hinge at midspan. Type 1 showed plastic local buckling on the compression side in the reduced thickness portion. Types 2 and 3 showed bulging of patch pates near front fillet welds that were close to the reduced thickness portion, and those front fillet welds failed when the load was around the maximum. In addition, for KW2B, KW3B1, and KW3B2, the groove weld on the compression side also failed at about the maximum load.

Table 5 shows that the initial stiffnesses from the tests are in good agreement with theoretical values, where the maximum relative difference is only 5%.

When the ultimate strength of each specimen is compared with that of Type 0 (KN0B), KA2B, KW2B, and KW3B1 were lower than KN0B by only a few percent, KW3B2 was lower by 10 percent, and KA3B was higher than KN0B by only a few percent. Therefore, for Type 2 and Type 3, the ultimate

Table 5. Stiffness, Ultimate Strength, and Deflection at Ultimate Strength (Four-point bending test)

Specimen	Type 0	Type 1	Type 2		Type 3			Type 4	
	KN0B	KN1B	KA2B (Air)	KW2B (Wet)	KA3B (Air)	KW3B1 (Wet)	KW3B2 (Wet)	KA4B (Air)	KW4B (Wet)
K_I (kN/mm) (% *error* from theory)	58.5 (*+3.2*)	45.1 (*-5.4*)	60.4 (*-2.3*)	62.8 (*+1.0*)	68.5 (*-3.3*)	69.9 (*-3.0*)	68.7 (*-2.2*)	94.8 (*-2.0*)	94.3 (*-1.2*)
P_{max} (kN)	614	303	585	595	633	583	552	890	873
δ_{max} (mm)	103	25.6	39.0	44.0	38.9	29.5	28.5	66.5	67.4
P_{max}/P_{y0}	1.58	0.78	1.51	1.53	1.63	1.50	1.42	2.29	2.25
δ_{max}/δ_{y0}	15.1	3.73	5.69	6.41	5.67	4.31	4.16	9.70	9.82

strength was recovered to the level of Type 0, except for KW3B2. The ultimate strength of Type 4, KA4B and KW4B, was about 1.4 times the ultimate strength of Type 0, implying that it was not an efficient design. It was also found that there was no significant difference between Type 2 and Type 3 because side fillet welds in Type 2, which were shorter than those required in the design, did not fail in the test. Type 2 and Type 4 specimens did not show significant differences in the load carrying capacity between the open air welding and the wet welding. However, Type 3 showed a 10% reduction in the ultimate strength of specimens repaired underwater. It is likely that this reduction was caused by the groove weld failure that occurred in KW3B1 and KW3B2.

4. CONCLUSIONS

In this study, stiffness and strength recoveries of steel pipes repaired with patch plates welded in the underwater wet environment were examined experimentally in compression and flexure. Test results showed that the initial stiffness was recovered as designed, and that the ultimate strength could be about 10% less than that of a repair carried out in the open air. These results are only applicable to the specific cases examined in this study. It is necessary to perform finite element analyses of repaired steel pipes with a wide range of different design parameters by strategically including characteristics of underwater wet welds.

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