Mechanical and Material Properties of Underwater Wet Fillet Welds for Offshore Steel Structure Repair

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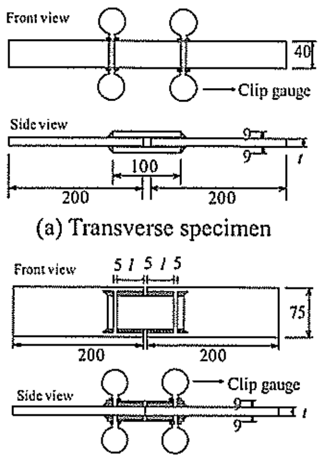
1 INTRODUCTION

Underwater wet welding has been used to build and repair offshore steel structures for decades. To evaluate current repair manual[1], which specifies the strength of underwater wet welds as 80% of that of in-air welds regardless of other design variables such as base steels and weld orientations, this paper presents an experimental study on mechanical properties of fourteen weld assemblies in terms of strength, ductility, and failure mode. Material properties such as Vickers hardness and microstructures of underwater welds are also examined.

2 EXPERIMENTAL PROGRAM

2.1 Test Specimens and Conditions According to JIS Z3131 and Z3132, fillet weld specimens as shown in Fig.1 are tested to failure. Weld deformations are measured by clip gauges placed at the ends of each weld bead. Test parameters include two weld orientations, four base steels, and two welding environments as shown in the specimen designation in Fig.2. The welding work is performed in a 3-m depth seawater pool with the welding conditions specified to simulate those used in real repair welding. Weld leg is specified as 6 mm, a typical size used in repair welding. Other details can be found in Ref.2). Table 1 shows chemical compositions of steels used in the test. Before the weld strength test, weld dimensions, as defined in Fig.3, are measured by a laser displacement sensor.



(a) Transverse specimen

(b) Longitudinal specimen

Fig.1 Specimens (in mm)*
*Curvature of pipe is not depicted

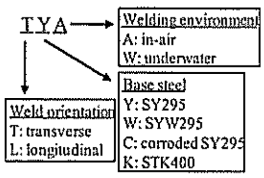


Fig.2 Specimen designation

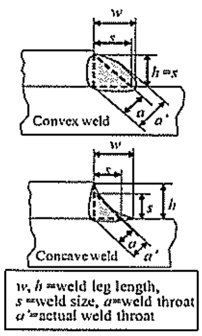


Fig.3 Weld dimensions

Table 1 Chemical compositions (wt-%) of steels

Material	C	Si	Mn	P	S	CE_{IIW}*
SY295	0.30	0.06	0.72	0.016	0.020	0.430
CSY295	0.27	0.02	0.96	0.013	0.019	0.433
SYW295	0.10	0.23	1.41	0.020	0.005	0.379
STK400	0.12	0.10	0.56	0.013	0.006	0.230
Electrode**	0.10	0.10	0.43	0.015	0.007	0.188

*CE_{IIW} = C+(Si+Mn)/6+(Cr+Mo+V)/5+(Ni+Cu)/15, only first two terms are used except SYW295.
**Catalogue values provided by the manufacturer.

2.2 Pre-test Investigations Roughness parameters are calculated for patched areas of corroded SY295 steel. Weld defects are inspected through the dye penetration test (JIA Z2343) and the radiographic examination (JIS Z3104). Visual inspection is also conducted to examine weld undercut and weld penetration at weld roots.

3 RESULTS AND DISCUSSIONS

3.1 Weld Mechanical Properties Weld strength is defined as Eq.(1) according to JIS Z3131 and Z3132, and weld ductility, a normalized factor, is defined as Eq.(2). In this paper, weld failure at weld deposit is referred to as DEPO failure, while failure at the boundary between weld deposit and base metal is referred to as BOND failure. The combination of the two is referred to as DEPO/BOND failure.

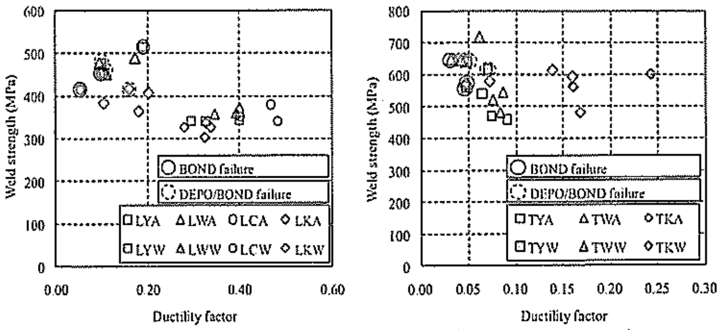
$$\sigma_w = \frac{P_{max}}{n\bar{a}l} \quad (1) \qquad \gamma = \frac{\Delta_{max}}{s} \quad (2)$$

where, σ_w is the average strength of fillet weld, P_{max} is the maximum carrying load of the specimen, $\bar{a}$ is the average throat size of all welds in each specimen, l is 20 mm for welds on corroded SY295, and 40 mm for the others, n is 2 for transverse weld specimens and 4 for longitudinal weld specimens, γ is the ductility factor, Δ_{max} is the measured weld deformation of the first fractured weld at its maximum applied load, and s is the weld size of the first fractured weld.

Eleven surface-breaking defects, including circular ones with a diameter 1 to 3 mm and line-shaped ones with a length around 2 mm, are found in eight out of twenty-two underwater weld specimens, and they are found to be no obvious correlation to weld failure. Moreover, underwater welds exhibit incomplete penetration at the weld root, and one weld exhibits incomplete fusion at corroded base plate.

(1) Weld strength and ductility The test results are plotted in Fig.4. The variations of strength and ductility of underwater welds are calculated in percent when compared with their counterpart in-air welds as shown in Fig.5. Underwater welds show a strength increase ranging from 6.9% to 41%, while ductility decrease is about 50% for most weld assemblies.

(2) Weld failure mode It is observed that all in-air welds failed at DEPO, while some underwater welds, as indicated with circles in Fig.4, fail either at BOND or with a combination of DEPO and BOND. Moreover, underwater welds on SY295 steels, with higher carbon equivalents around



(a) Longitudinal specimen (b) Transverse specimen

Fig.4 Weld strength versus ductility factor

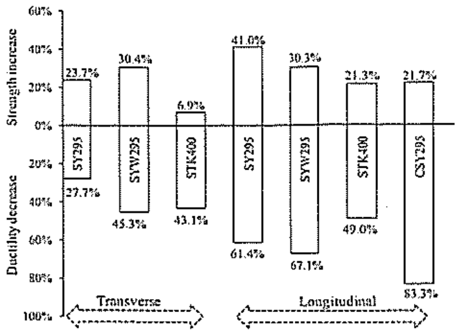


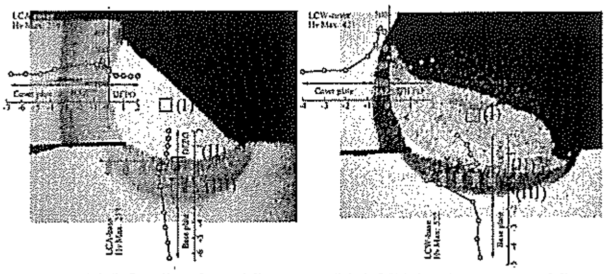
Fig.5 Relative changes of strength and ductility from in-air welds to underwater welds

0.430, are more likely to show BOND related failures than those on SYW295 and STK400 steels, with lower carbon equivalents at 0.379 and 0.230, respectively.

(3) Corrosion effects The correlation between surface roughness parameters and weld strength as well as ductility is not obvious among five corroded specimens, although one weld at LCW specimen is observed to have incomplete fusion due to deep corrosion pits at base steel.

3.2 Weld Material Properties To better understand underwater welds from material aspects, Vickers hardness test and metallographic examinations are performed on weld specimens produced simultaneously with those for the strength tests to ensure the same welding conditions.

(1) Hardness distribution Fig.6 shows photos of polished and etched cross sections of LCA and LCW welds, presenting general features of in-air and underwater welds with Vickers hardness results superimposed. Hardness peaks can be found in the coarse grained region of heat affected zone (HAZ) in both in-air and underwater welds. Hardness results of all specimens suggest that due to the rapid quenching in the wet environment, underwater welds have a smaller HAZ size of 1 to 2 mm and higher hardness of 310 to 526 Hv, whereas they are 3 to 4 mm and 198 to 375 Hv, respectively for in-air welds. The increases of hardness peak from in-air welds to underwater welds are 72%, 35%, and 49% for welds on SY295, SYW295, and STK400 steels, respectively.



(a) LCA (in-air weld) (b) LCW (underwater weld)

Fig.6 Hardness distribution in welds

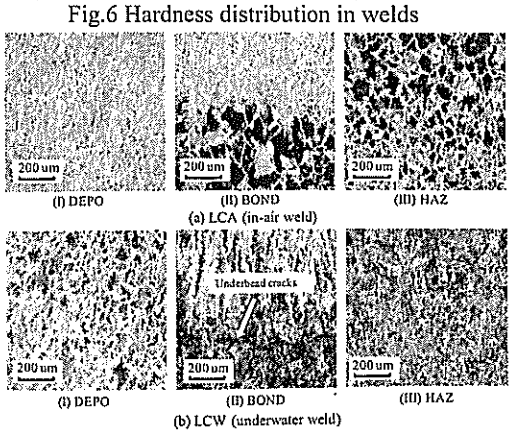


Fig.7 Weld microstructures

(2) Weld microstructures Three windows in each photo of Fig.6 signify the areas where microstructure images, shown in Fig.7, are taken. The microstructures of DEPO are shown in Fig.7(a)(I) and 7(b)(I). DEPO in LCA is mainly composed of ferrite and pearlite with 150 Hv, and DEPO in LCW has similar compositions but with 300 Hv. HAZ in LCA shown in Fig.7(a)(III), is composed of ferrite and pearlite with 200 Hv, while HAZ in LCW, as shown in Fig.7(b)(III), is dominated by martensite with 500 Hv. Furthermore, underwater welds are observed to have underbead cracks at BOND as indicated in Fig.7(b)(II). The distinct mechanical mismatching over base steel with 150 Hv is reported to have detrimental effects to weld joints with presence of cracks in BOND and HAZ[3].

4 CONCLUSIONS

Underwater fillet welds have larger strength but smaller ductility than in-air welds. Strength increases vary from 6.9% to 41%, while ductility decrease is about 50% for the most weld assemblies. Underwater welds on SY295 and SYW295 steels are more susceptible to BOND related failures than those on STK400 steel due to higher carbon content.

REFERENCES

1) Coastal Development Institute of Technology, Port Steel Structure Corrosion-Prevention and Repair Manual, Coastal Development Institute of Technology, Japan (1997).

2) X. Chen, Y. Kitane, and Y. Itoh, Mechanical Properties of Fillet Weld Joints by Underwater Wet Welding in Repairing Corrosion-Damaged Offshore Steel Structures, Journal of Structural Engineering, JSCE, **56A** (2010) (*in press*).

3) Z.L. Zhang, C. Thaulow, and M. Hauge, Effects of crack size and weld metal mismatch on the HAZ cleavage toughness of wide plates, Engineering Fracture Mechanics, **57**, 6 (1997).