NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 110 SEPTEMBER 2015

Technical Report

UDC 621 . 311 . 24 : 669 . 14 . 018 . 292 : 539 . 43

Steel Plates and Fatigue Solution for Offshore Wind Turbines in the Fukushima Floating Offshore Wind Farm Demonstration Project

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Abstract

Floating offshore wind farms are essential for increasing the efficiency of wind power generation in Japan because ocean areas that have high wind potential are spread over Japan's deep-sea areas. The Ministry of Economy, Trade and Industry in Japan (METI) launched the Fukushima Floating Offshore Wind Farm Demonstration Project in 2012. The aim of this project is to strengthen Japan's competitive position in the global wind farm market. Nippon Steel & Sumitomo Metal Corporation participated in the project, and demonstrated that both TMCP steel plates for large heat input welding and UIT technology for solving the problems associated with fatigue are useful in offshore wind turbine structures.

1. Introduction

Wind and solar energy are promising sources of renewable energy for power generation. Wind power plants can be constructed either on land or offshore, but offshore locations are considered more suitable for wind power generation because offshore wind is stronger and less turbulent than onshore wind.

Many bottom-mounted offshore wind turbines have been constructed in Europe. This is because the seas are shallow there in many places, and even at 100 km or more away from the coast, the water depth is often less than 60 m. Japan is surrounded by the sea, and offshore wind turbines are expected to play a significant role in power generation, but the sea bottoms in Japan are generally deeper than those in Europe, and it is necessary to make practical floating wind power plants.

As a member of an 11-party consortium for the Fukushima Floating Offshore Wind Farm Demonstration Project, abbreviated as Fukushima FORWARD (suggesting the recovery from the Great East Japan Earthquake in 2011),[1] under the auspices of the Ministry of Economy, Trade and Industry, Nippon Steel & Sumitomo Metal Corporation has undertaken studies regarding the floating platforms for offshore wind farms since 2011.

While floating offshore wind turbine generators of 2 MW class have already been tested in Norway and Portugal, what is envisaged in the first stage of the Fukushima FORWARD project is the world's first floating offshore wind farm complex composed of a wind power plant and a substation. Furthermore, in the second stage, the complex is to have a 7 MW plant, the world's largest class. Thus, the project is very important for the country to stand at the top in the field of floating offshore wind farms.

This paper presents the outlines of the study for the project, and principal items of the study subjects of the Company, namely high tensile strength steel plates produced by the thermo-mechanical control process (TMCP) for large-heat-input welding and the application of a fatigue solution.

2. Outlines of Demonstration Study

As shown in **Fig. 1**,[1] the Fukushima FORWARD project is divided into Phase 1 (2011–2013, in terms of fiscal year starting from

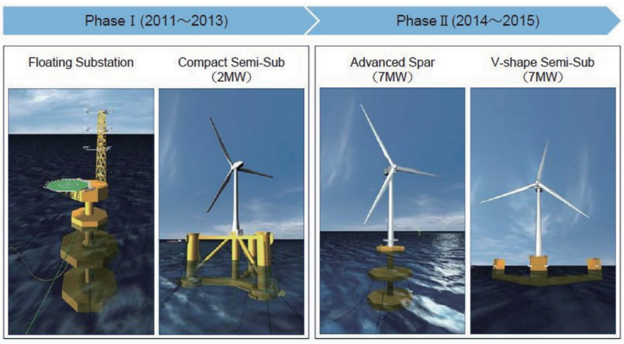

Fig. 1 Scope of Fukushima FORWARD project [1]

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Table 1 Project member and main role [1]

FORWARD member	Main role
Marubeni Corporation [Project integrator]	Feasibility study, Approval and licensing, O & M, Collaboration with fishery industry
The University of Tokyo [Technical adviser]	Metocean measurement and prediction Technology, Marine navigation safety, Public relation
Mitsubishi Corporation	Coordination for grid integration, Environmental impact assessment
Mitsubishi Heavy industries, Ltd.	V-shape semi-sub(7MW)
Japan Marine United Corporation	Advanced Spar, Floating Substation
Mitsui Engineering & Shipbuilding Co., Ltd.	Compact Semi-sub(2MW)
Nippon Steel & Sumitomo Metal	Advanced steel material
Hitachi Ltd.	Floating Substation
Furukawa Electric Co., Ltd.	Large capacity undersea cable
Shimizu Corporation	Pre-survey of ocean area, Construction technology
Mizuho Information & Research institute, Inc	Documentation, Committee Operation

April) and Phase 2 (2014 to 2015); in Phase 1, a 2 MW downwind type floating wind power plant, named Fukushima Mirai (future), and a floating substation to boost the power from 22 kV to 66 kV, named Fukushima Kizuna (the bonds of friendship), the world first example of floating substation, were installed, and in Phase 2, two units of 7 MW floating wind power plants are being constructed.

Table 1 [1] shows the roles of the consortium members. Nippon Steel & Sumitomo Metal is responsible for the development of high-performance steels for floating wind turbine facilities and has been conducting the demonstration studies on the following four subjects:

(1) Application of high tensile strength steel plates to floating offshore wind turbine structures (mainly for high-efficiency welding using TMCP steel plates for large-heat-input welding).
(2) Application of fatigue solution to floating offshore wind turbine structures (mainly for the improvement of fatigue strength in welded joints by the Ultrasonic Impact Treatment (UIT), whose technology is possessed by UIT, L. L. C. in the US.
(3) Use of mooring chains to anchor floating units to the sea bottom (for the improvement of resistance to wear and fatigue using high-strength steel, etc.).
(4) Corrosion resistance of steel material (mainly for the evaluation of corrosion characteristics in different types of stainless steels by exposure testing).

3. TMCP Steel for Large-heat-input Welding

In general, the support structures for offshore wind turbine generators are more costly than those for others on land, and in the case of bottom-mounted offshore turbines, larger support structures are required as the water depth increases, which means increasingly higher costs in the future.[2] Typical fixed support structures include mono-piles and jackets, and thicker steel plates (40 mm or more) are used for these structures in the latest trend for larger turbines. For floating wind turbines, support structures of spar type, semi-submersible (Semi-Sub) type, etc., to which the technologies for ships and marine structures are applicable, are being considered. The larger the turbine, the thicker the steel plates for core structural parts, as is the case with fixed ones. It follows therefore that, in view of the increasing number of large wind turbines, cost reduction of welding of thick plates, or efficiency improvement of welding work, is a development subject essential for expanding offshore wind turbine power generation, either fixed or floating.

Outside Japan, higher welding efficiency has been pursued for building the support structures for offshore wind turbine generators by increased welding speed [3] and use of narrow grooves.[4] In Japan, in contrast, large-heat input welding, which allows a large decrease in the number of passes, has been widely practiced in fields such as shipbuilding and building construction as a high-efficient and easily controllable approach.[5] However, note that with increasing heat input, the holding time at high temperatures is longer and the cooling rate after the welding is lower in the heat affected zones (HAZ), and consequently, grains grow coarse and it not easy to secure high toughness in the temperature range of 0 to −40°C, which is essential for the structures for offshore wind turbines. Nippon Steel & Sumitomo Metal has developed a technology called the “high HAZ toughness technology with fine microstructure imparted by fine particles (HTUFF™),” [6–8] whereby grain coarsening in HAZ is prevented by thermally stable nanoparticles at high temperatures; this exactly meets the above requirement. In fact, heavy plates for large-heat-input welding manufactured through TMCP and application of HTUFF have been used for the support structures for fixed offshore wind turbines.[9]

In the present study, the characteristics of joints of TMCP plates welded under large heat input were examined considering their application to the support structures for floating offshore wind turbines.

3.1 Test method

Heavy plates of grades KD36-TM and KE36-TM, high-tensile steels for ship hulls under Class NK, most likely to be used for the core parts of the floating structures for wind turbines, were selected as the specimens. While KD36-TM is a conventional high-HAZ-toughness steel using TiN, KE36-TM is another conventional steel to which the said HTUFF is applied. Considering the plate thicknesses of real floating structures and practicable welding methods, 25-mm plates of the former were selected as the specimens for general structural parts, and 40- and 50-mm plates of the latter as those for important parts. **Tables 2** and **3** list the target properties and the chemical compositions, respectively, of the specimen plates. Three methods of high-efficiency welding suitable for the manufacture of the floating structure were employed for the test: one-side submerged arc welding (called FCB in the figures and tables), electrogas arc welding (EGW), and two-side submerged arc welding (SAW). How these welding methods were employed in the present test is given in **Table 4**.

In principle, the properties of welded joints were evaluated as follows according to Part M “Welding” of the Rules and Guidance for the Survey and Construction of Steel Ships of Class NK: the existence or otherwise of defects and the quality of welding was evaluated by macroscopic test, tensile properties by tensile test using U2A test pieces cut out in right angles to the weld line, and toughness by Charpy impact test using V-notch test pieces (according to JIS Z 2242) cut out likewise. **Figure 2** illustrates the positions of the test pieces in welded joints.

Table 2 Target properties

Steel	:	KD36-TM, KE36-TM
Tensile properties	:	YS ≧ 355MPa, TS 490–620MPa
Thickness	:	25–50mm
Test temperature of Charpy impact test	:	KD36-TM: −20°C in base metal, 0°C in welding joint KE36-TM: −40°C in base metal, −20°C in welding joint
Welding method	:	FCB, EGW, SAW
Maximum welding heat input	:	10–31 kJ/mm

Table 3 Chemical compositions (mass%)

No.	Steel	Thicness (mm)	C	Si	Mn	P	S	Others	Ceq
A	KD36-TM	25	0.13	0.22	1.18	0.011	0.003	Nb, Ti	0.33
B	KE36-TM	40	0.11	0.29	1.30	0.010	0.002	Nb, Ti	0.33
C	KE36-TM	50	0.12	0.29	1.31	0.008	0.002	Nb, Ti	0.34

Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15

Table 4 Welding methods

No.	Steel	Thicness (mm)	Welding conditions		
			Position	Welding process	Heat input
A1	KD36-TM	25	Flat	FCB	16 kJ/mm
A2			Vertical up	EGW	10–11 kJ/mm
B1	KE36-TM	40	Flat	FCB	31 kJ/mm
B2			Flat (two-run welding)	SAW	12 kJ/mm
C1	KE36-TM	50	Vertical up	EGW	28 kJ/mm

3.2 Test results and discussion

Table 5 shows the results of the tensile and Charpy impact tests of the specimen plates. All the target values were satisfactorily cleared.

Typical examples of sectional photographs of the joints welded by different welding methods are given in **Fig. 3**. All the joints exhibit satisfactory penetration, and no cracks, insufficient penetration or fusion, or any other harmful defects were found.

Table 6 shows the results of the tensile test of the welded joints. All the joints satisfied the relevant tensile strength figures (490–620 MPa according to Part K of the said Rules and Guidance of Class NK; all test pieces finally broke at the base metal, which evidences good joint performance.

The Charpy impact values of the joints are given in **Fig. 4**; all the test pieces cleared the stipulation in Part M of the said Rules and Guidance, evidencing good impact characteristics.

Figure 5 shows typical sectional photomicrographs of the welded joints of the test pieces. All the joints proved to have good microstructures; the photos confirm that, near the fusion line (FL) especially of KE36-TM, to which HTUFF was applied, the coarsening of prior γ grains is clearly suppressed, and grain boundary ferrite and bainite, which form during cooling, are prevented from coarsening as well.

Figure 6 shows the relationship between weld heat input and the fracture appearance transition temperature (vTrs) at the FL on the root side (see Fig. 2(a)), the part of a welded joint where impact toughness is most likely to fall, of each of the steels. Note that the plotting of SAW, which was applied to double V grooves only, represents the FL on the cap side (see Fig. 2(b)). The vTrs value of either of the steels was equal to or below the assessment temperature, which evidenced good impact characteristics; note here that KE36-TM, the HTUFF steel, exhibited generally better values of vTrs than those of KD36-TM, the conventional TiN steel. In consideration of the facts that the chemical compositions of the two are substantially the same and that, in terms of the microstructure of HAZ, the crystal grains of the latter are finer than those of the former, the effect of

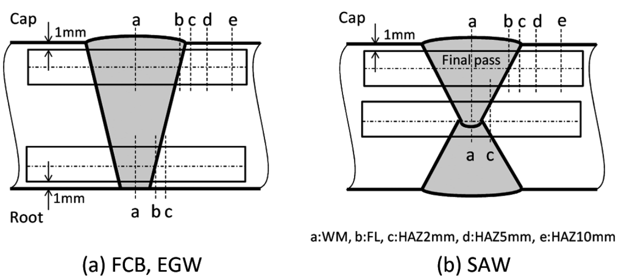


Fig. 2 Sampling of test specimens from welded joints

Table 5 Mechanical properties of developed steel plates

No.	Steel	Thicness (mm)	Tensile test				Charpy impact test		
			Direction, location	YS (MPa)	TS (MPa)	EL (%)	Direction, location	Temp. (°C)	vE Min./Ave. (J)
A	KD36-TM	25	T, 1/4t	419	527	24	L, surface	−20	291/310
B	KE36-TM	40	T, 1/4t	429	557	28	L, surface	−40	256/272
C	KE36-TM	50	T, 1/4t	409	539	27	L, 1/4t	−40	271/299

T: Transverse direction, t: Thickness, YS: Yield stress, TS: Tencile strength, EL: Elongation, L: Longitudinal direction

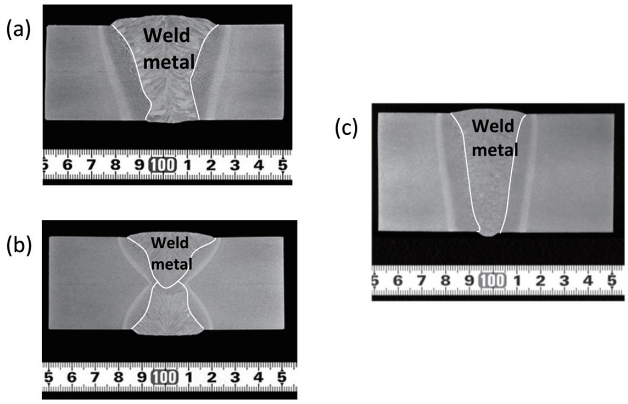


Fig. 3 Macroscopic appearances of welded joints
(a) FCB, B1, (b) SAW, B2, (c) EGW, C1

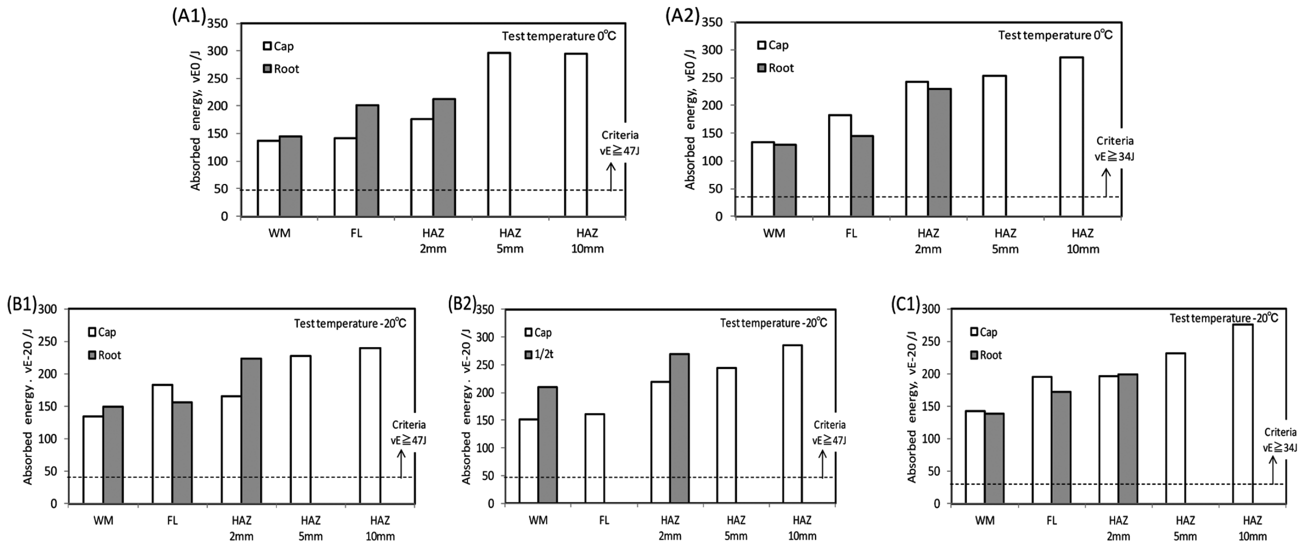
HTUFF to prevent the coarsening of HAZ structure is greatly effective at improving the vTrs of welded joints.

3.3 Advantages of large-heat-input welding

The authors examined the effects of large-heat-input welding on

Table 6 Results of welded joint tensile tests

No.	Steel	Tensile strength (MPa)	Fracture position
A1	KD36-TM	540	Base metal
A2	KD36-TM	561	Base metal
B1	KE36-TM	533	Base metal
B2	KE36-TM	565	Base metal
C1	KE36-TM	577	Base metal
Class NK M	–	490–620	–



(A1) KD36-TM, FCB, (A2) KD36-TM, EGW, (B1) KE36-TM, FCB, (B2) KE36-TM, SAW, (C1) KE36-TM, EGW

Fig. 4 Charpy impact toughness of welded joints

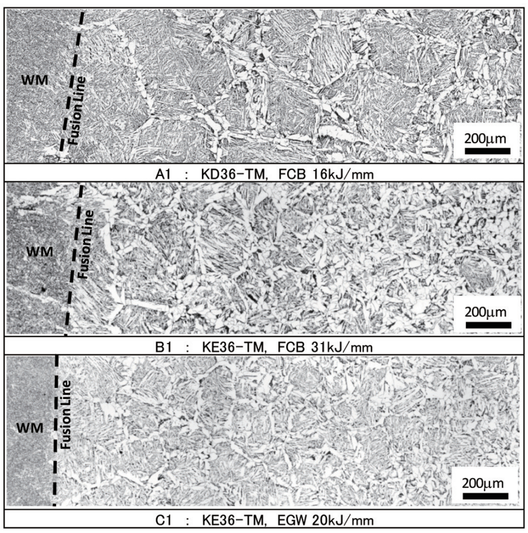


Fig. 5 Microstructures of welded joints

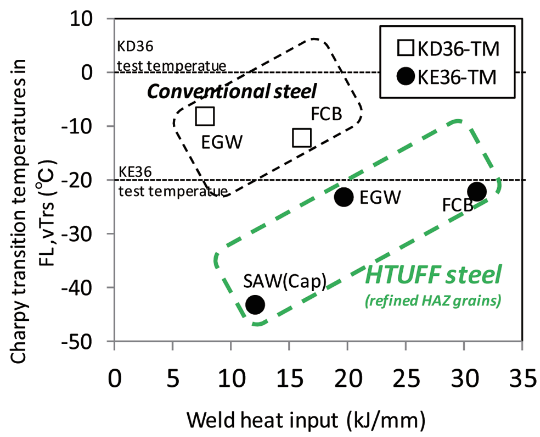


Fig. 6 Relationship between Charpy vTrs in FL (root) and weld heat input

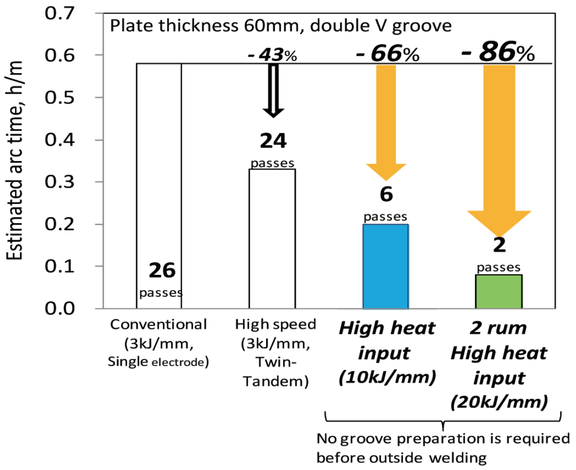


Fig. 7 Advantages of high heat input SAW in arc time

welding work efficiency. **Figure 7** shows the estimation of the arc time (per meter) and the number of passes required for welding the entire thickness of double-V-groove joints by two-side SAW, widely employed for the bases of offshore wind turbines. Compared with twin-wire, single electrode SAW (the left-hand-most bar) commonly used for mono-pile foundations, the arc time can be considerably reduced by high-speed SAW; however, when the heat input is increased to 10 kJ/mm, it is shortened by 66%, and at 20 kJ/mm, by as much as 86%. In addition, large-heat-input welding offers further advantages in relation to preparation work, which is not at all negligible in actual field work; such include elimination of the groove forming on the outside after welding from inside and less auxiliary work items before every pass. The above indicates that the use of TMCP steels for large-heat-input welding results in the significant reduction of the welding time

3.4 Summary

To collect data on the use of high-tensile steel plates for the construction of a large-scale floating offshore wind farm, the world's first example of the kind, steel plates of five different types were welded employing large-heat-input welding processes suitable for manufacturing floating offshore structures, and the characteristics of the joints were examined. As a result, all the welded joints proved to have good properties in every evaluation item. It has been made clear that KE36-TM, an HTUFF steel, maintains good HAZ toughness even under large heat input for welding. It has been demonstrated in addition that an increase in heat input is significantly effective at enhancing the efficiency of high-speed SAW, which is widely employed for the support structures for offshore wind farms.

4. Fatigue Solution

Floating offshore wind farms are subject to variable loading by ocean winds and rotor vibrations, which are typical of wind turbines, as well as sea waves, which are inevitable in floating structures. Some structural members accordingly undergo complicated cyclic stress in the wide frequency range, and careful fatigue design is required for the structural components of high stress concentration to secure design life. On the other hand, the use of high-tensile strength steels can be required for weight reduction for constructing large floating offshore wind turbines, but high tensile strength steel does not result in the high fatigue strength of welded joints. Fatigue solutions are useful technologies for taking advantage of using high tensile strength steels and are measures to enhance the fatigue strength of welded joints; such measures are referred to as fatigue solutions in this technical report.

Grinding, additional welding, and TIG dressing have been investigated and applied as conventional fatigue solution to welded structures such as ships and bridges; however, their effects on fatigue mostly result from decrease in stress concentration caused by toe shape improvement. Another fatigue solution of UIT contributes to the improvement of residual stress and grain refining as well as toe shape improvement, and its superior effect on fatigue strength improvement effect is being appreciated through applications to ships and bridges.[10–17] While the fatigue property of welded joints with UIT has been studied for conventional welded structures such as ships and bridges,[12–16] it has not as yet been studied for floating offshore wind turbine structures, which constitute an entirely new type of welded structure. These structures, in addition to being subject to the abovementioned complicated cyclic stress, are often installed at positions where access is not easy, and high fatigue property is required of them to reduce maintenance costs.

In this study, the authors focused on a corner boxing bracket end between a floating horizontal deck plate and a wind turbine tower, which is one of the severest welded joints for fatigue design requirement, and prepared large-scale structural model fatigue specimens simulating a part of wind turbine corner boxing bracket ends. High tensile strength TMCP steel plates were used for the specimens, and the effect of UIT on fatigue property improvement was investigated for the specimens.

4.1 Testing methodology

4.1.1 Steel plates used for tests

High tensile strength steel of YP355, whose specified minimum yield stress, SMYS, is 355 MPa, has been used for most of the floating structures in the present project, but in the future, higher strength steel of YP460, whose SMYS is 460 MPa, is expected to be used for weight reduction and for constructing a lot of large offshore wind power plants efficiently. YP460 steel plates were used for manufacturing fatigue specimens in this study. **Table 7** shows the chemical compositions and the mechanical properties of the plates used.

4.1.2 Large-scale structural model fatigue specimens

As stated earlier, the corner boxing bracket edge between the floating horizontal deck plate and the wind turbine tower was selected as the location of the fatigue crack initiation. A large-scale struc-

Table 7 YP460 steel plates used for large-scale structural fatigue specimens

Thickness (mm)	Chemical compositions (%)					Mechanical properties		
	C	Si	Mn	P	S	Yield stress (MPa)	Tensile strength (MPa)	Elongation (%)
25	0.09	0.29	1.51	0.013	0.002	564	623	20
	0.09	0.29	1.51	0.012	0.002	584	657	19
50	0.10	0.05	1.42	0.009	0.004	527	620	19

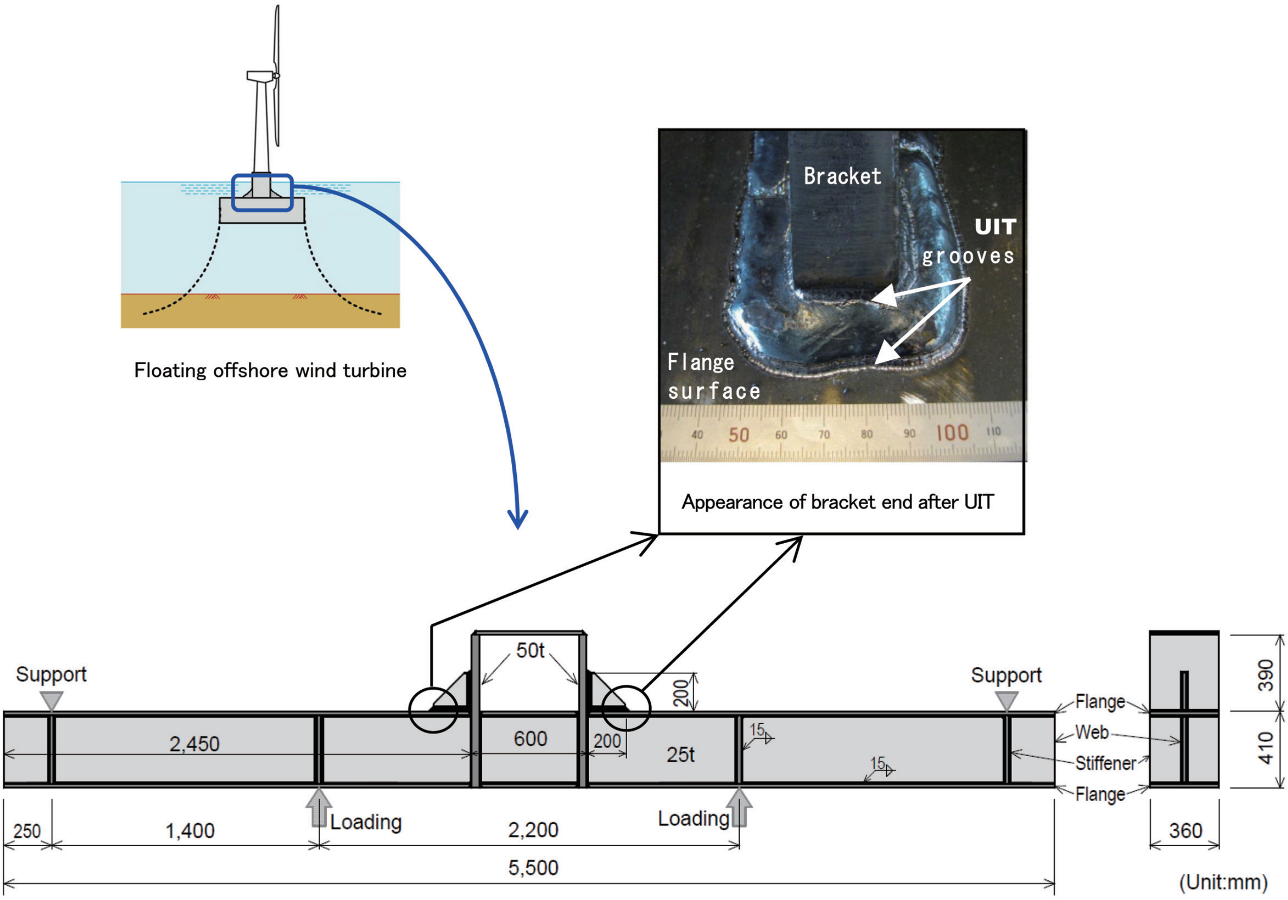


Fig. 8 Large-scale structural fatigue specimen

tural model fatigue specimen comprising a horizontal member simulating a floating deck plate and a vertical member simulating a tower was designed for four-point-bend testing, and the specimen has two brackets (see **Fig. 8**). The horizontal member was a welded beam of an I-section composed of an upper and a lower flange, a web and stiffeners, and to simulate the tower, two vertical plates penetrating the horizontal member were placed and tied to each other at the top with a horizontal plate. Four fatigue specimens, each of which was 5 500 mm in length, were manufactured by gas-shield arc welding using flux-cored wires for 590 MPa class tensile strength and CO_2 as the shielding gas. As is the common practice of shipbuilding, all the welding was fillet welding. Of the four specimens, two underwent UIT along the corner boxing weld toes on the bracket side and the flange (horizontal member) side before fatigue testing, and the other two were used for as-welded (AW) bracket ends without UIT.

Note that to prevent fatigue cracks during the tests, UIT was applied to all the welded joints of the four specimens, except for the weld toes along the corner boxing bracket edges of the AW specimens. As an UIT equipment, ESONIX® 27 UIS manufactured by Applied Ultrasonics in the US was used in this study. The operating frequency of the ultrasonic generator was 27 kHz, the diameter of the indenter pin was 3 mm, and the tip radius of the indenter pin was also 3 mm.

4.1.3 Fatigue tests

Large-scale structural model fatigue tests were conducted using an electro-hydraulic fatigue test machine with the load capacity of 2.5 MN. The nominal stress σ on the flange surface between the two loading points was calculated by the elastic four-point bend calculation of the I-section beam, and its range $\Delta\sigma$ was set at two different levels for two specimens in each type of specimen, UIT or AW. The fatigue testing was conducted in air at room temperature, and the load was applied with sinusoidal waveform, where the stress ratio R was 0.1 and the frequency f was 0.5–1.0 Hz. The local strain range was measured in the longitudinal direction through an uniaxial elastic strain gauge attached 5 mm away from the center of the UIT groove or the AW toe for each bracket end, and the fatigue testing was continued until the local strain range decreased by 5% of the initial value on either of the sides. Fatigue crack initiation life Ni was defined as the number of cycles to fatigue crack initiation detected at the weld toe or the UIT groove by dye penetrant testing.

4.2 Test results and discussion

The relationship between $\Delta\sigma$ and N_i is shown in **Fig. 9**. The UIT specimens had higher fatigue strength and longer fatigue life than the AW specimens did. Note here that, when a fatigue crack was found at the weld of one of the bracket ends of a UIT specimen, it was repaired by welding, and the test was continued for the other bracket end; thus two plots were obtained with each of the UIT specimens. Note also that, since the number of the plots was insufficient for fitting an S–N curve for each type of specimen, the slope m of each S–N curve was determined using the same m as that of DNV-PR-C203,[18] $m = 5$, the value for hammer peened welded joints for the UIT specimens, wherein m is known to be larger than in AW joints owing to the compressive residual stress,[17] and $m = 3$ for the AW specimens with tensile residual stress. As a result, each S–N

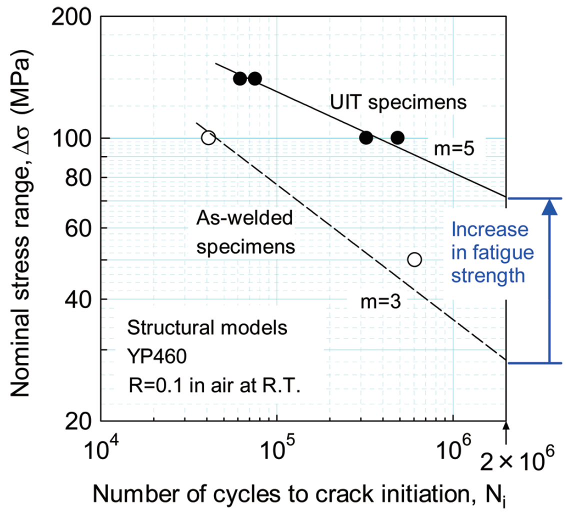


Fig. 9 Fatigue properties of large-scale structural specimens

curve fitting was closely located to the experimental plots for each type of specimen. The curves show that UIT has a significant effect on fatigue property improvement, especially in the low $\Delta\sigma$ region.

What designers use in the practical fatigue assessment, however, is not such test results obtained using large structural models but authorized fatigue design curves. When one of the characteristic fatigue strengths in the design curves, which is defined by the stress range at 2 million cycles, is used for comparison between two types of specimen, the fatigue strength of the UIT specimens is more than twice as high as that of the AW specimens at 2 million cycles. This indicates that UIT significantly improves the fatigue strength of welded joints of not only ships and bridges but also floating offshore wind turbine structures.

4.3 Summary

In the present study, the effect of UIT on fatigue property improvement in corner boxing bracket ends was investigated using large-scale structural model fatigue specimens simulating floating offshore wind turbine structures. As a result, UIT specimens demonstrated higher fatigue strength and longer fatigue life than those of AW specimens. According to the comparison of obtained fatigue strength at 2×10^6 cycles, welded joints with UIT have double the fatigue strength of AW joints, and UIT is expected to significantly improve the fatigue properties of floating offshore wind turbine structures.

5. Concluding Remarks

This technical report first summarizes the Fukushima floating offshore wind farm demonstration project, and then demonstrates the results of the study on the applicability of TMCP steel plates for large-heat-input welding and a fatigue solution of UIT to floating offshore wind turbine structures. The TMCP plates, which were evaluated under the conditions of large-heat-input welding that were supposed to be employed for floating offshore wind turbines, proved to have sufficiently good properties. Regarding the application of UIT, large-scale structural model fatigue specimens with corner boxing bracket ends were manufactured using high-tensile strength TMCP steel plates to simulate a high stress concentration welded joint between a floating horizontal deck plate and a wind turbine tower. Their fatigue tests demonstrated that UIT remarkably improved the fatigue properties of welded joints. These technologies are expected to greatly enhance the construction efficiency and endurance of floating offshore wind turbine structures, and can significantly contribute to the expansion of floating offshore wind power plants in the future.

References

1) Fukushima Offshore Wind Consortium: Fukushima Floating Offshore Wind Farm Demonstration Project (Fukushima FORWARD). 2012
2) Ishihara, T.: Sangyo-to-Kankyo. 6, 35 (2011) (in Japanese)
3) Gehring, M.: Welding in the World. 52, 545–550 (2008)
4) Nakazawa, H., Nagasaki, H.: J. Japan Welding Society (JWS). 79 (7), 22 (2010)
5) Sasaki, K., Suda, K., Motomatsu, R., Hashiba, Y., Ohkita, S., Imai, S.: Nippon Steel Technical Report. (90), 67 (2004), for example
6) Kojima, A., Uemori, R., Minagawa, M., Hoshino, M., Ichikawa, K.: Materia Japan. 42, 67 (2003)
7) Kojima, A., Kiyose, A., Uemori, R., Minagawa, M., Hoshino, M., Nakashima, T., Ishida, K., Yasui, H.: Nippon Steel Technical Report. (90), 2 (2004)
8) Minagawa, M., Ishida, K., Funatsu, Y., Imai, S.: Nippon Steel Technical Report. (90), 7 (2004)
9) Homma, R., Hoshino, M., Nakashima, K., Shishibori, A., Kojima, K., Nishimura, S., Bockelmann, M.: Proc. of EWEA Offshore 2013. 2013, p. 104
10) Statnikov, E. S.: Comparison of Post Weld Deformation Methods for Increase in Fatigue Strength of Welded Joints. IIW Doc. XII-1668-97, 1997
11) Haagensen, P. J., Statnikov, E. S., Lopez-Martinez, L.: Introductory Fatigue Tests on Welded Joints in High Strength Steel and Aluminium Improved by Various Methods including Ultrasonic Impact Treatment (UIT). IIW Doc. XIII 1748-98, 1998
12) Shimanuki, H., Nose, T.: Effect of Ultrasonic Impact Treatment on Fatigue Properties of Structural Model. Preprints National Meeting JWS. Vol. 81, 2007, p. 342 (in Japanese)
13) Nose, T., Shimanuki, H.: Experiment and Analysis of Influence of Ultrasonic Peening on Fatigue Life of Pad Welded Joints. Transactions of Japan Society of Mechanical Engineers, Series A. 74 (737), 166–167 (2008) (in Japanese)
14) Shimanuki, H., Ohkawa, T., Nose, T.: Proc. 2009 Welded Structure Symposium. 2009, p. 479–482 (in Japanese)
15) Mori, T., Shimanuki, H., Tanaka, M.: Effect of UIT on Fatigue Strength of Web-gusset Welded Joints Considering Service Condition of Steel Structures. Welding in the World. 56, 141–149 (2012)
16) Okawa, T., Shimanuki, H., Funatsu, Y., Nose, T., Sumi, Y.: Effect of Preload and Stress Ratio on Fatigue Strength of Welded Joints Improved by Ultrasonic Impact Treatment. Welding in the World. 57, 235–241 (2013)
17) Shimanuki, H., Tanaka, M.: Application of Fatigue Crack Initiation Suppression Technology of Welded Structures by UIT, Nippon Steel & Sumitomo Metal Technical Report. (110), (2015)
18) Det Norske Veritas: Fatigue Design of Offshore Steel Structures. DNV-RP-C203, 2011

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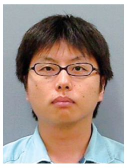

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