Enhancing fatigue strength by Ultrasonic Impact Treatment for welded joints of offshore structures

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ABSTRACT: This paper summarises fatigue tests on Y-joints to estimate the influence of a post weld treatment method called Ultrasonic Impact Treatment. With this method the fatigue resistance could be increased significantly. Furthermore, tubular joints of tripod structures for offshore wind energy converters are analysed with numerical simulations to judge these welded joints with the hot-spot-concept. The stress concentration factor for the treated weld toe geometry was determined numerically and compared to experimental results.

1 INTRODUCTION

For the planned offshore wind farm "Kriegers Flak I" in the Baltic Sea a fatigue design study was carried out including experimental and numerical investigations for welded joints of a tripod. A tripod is one kind of a supporting structure for wind energy converter as shown in Figure 1. The calculations were based on Baltic Sea conditions with 25 m water depth and for a 2 MW turbine. The welded joints were designed for a fatigue life of 20 years with numerical simulation based on the hot-spot-concept.

Furthermore experiments were carried out to estimate the fatigue resistance for such welded joints. Because of large dimensions for tripods the fatigue tests can't be performed in real scale.

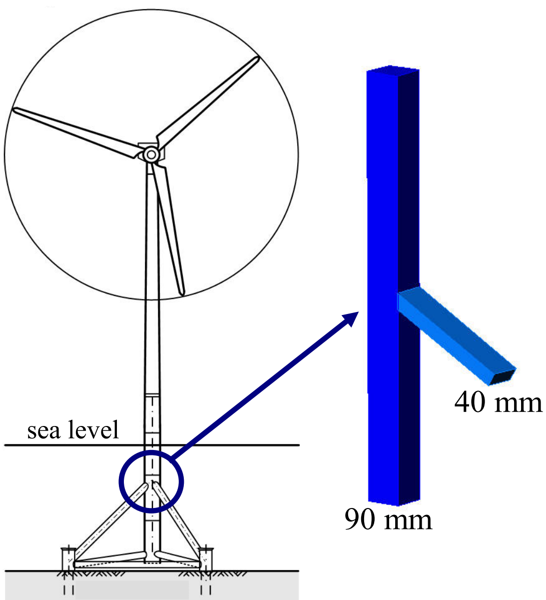

Figure 1. Offshore wind energy converter with tripod as support structure and Y-joint for experiments

Therefore 12 Y-joints were tested with $t_c = 90$ mm thickness for the chord and $t_b = 40$ mm for the brace welded in an angle of $\theta = 60°$. The plate thicknesses are comparable to those of tripods. The objective of these tests was to check the fatigue resistance for welded joints with thick plates. Additionally the influence of post weld treatment by Ultrasonic Impact Treatment (UIT) was estimated. This method introduces compressive stresses and plastic deformations at the weld toe to reduce residual stresses and stress concentrations. Because of these effects the fatigue strength increases significantly compared to as welded conditions.

Furthermore different types of tubular joints for offshore structures were investigated with numerical simulations to estimate the fatigue limit state for both conditions, as welded and treated by UIT. The stress concentration factors (SCF) for the treated weld toe geometry were determined numerically using sub-model analysis and compared to experimental results. Finally a comparison between welded and cast iron joints was carried out in a fatigue design study under consideration of UIT-effects.

2 EXPERIMENTS WITH Y-JOINTS AND UIT

2.1 *Test specimen*

The test specimens comprise of Y-joints with $t_c = 90$ mm thickness for the chord and $t_b = 40$ mm for the brace. Chord and brace were welded in an angle of 60° with fillet welds. The Y-joints were fabricated of steel S 355 J2G3. Chemical and mechanical properties of this steel are presented in Tables 1 and 2.

Table 1. Chemical composition of material S355 J2G3 in [%]

C	Si	Mn	P	S	N	Cr	Ni
0.16	0.34	1.43	0.014	0.004	0.006	0.07	0.06

Table 2. Mechanical properties of material S355 J2G3

Yield strength $R_{e,H}$	Ultimate strength R_m	Elongation at failure A_5	Impact ductility KV
[N/mm²]	[N/mm²]	[%]	[J, -40°C]
386	537	23.5	106

The specimen geometry with detailed dimensions of these welded joints is shown in Figure 2.

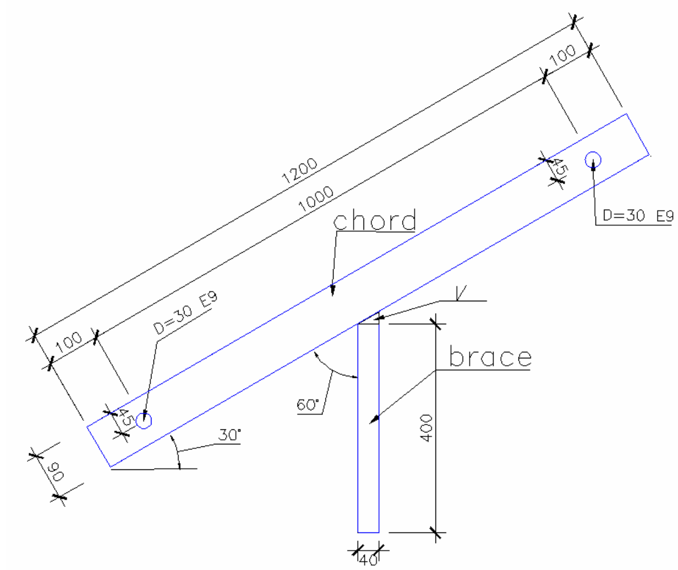

Figure 2. Test specimen

2.2 *Experimental Setup for fatigue testing*

Fatigue testing was performed using a 600 kN servo-hydraulic test frame. The experiments were carried out up to 2 million cycles with test frequencies between $f_P = 3 – 5$ Hz depending on the value of the dynamic force. The test setup consisted of four columns with base plates and two horizontal bracing members. The Y-joint was supported by bolted connections at both ends of the chord. The position of the brace was vertically to fix the end of the brace in the testing machine.

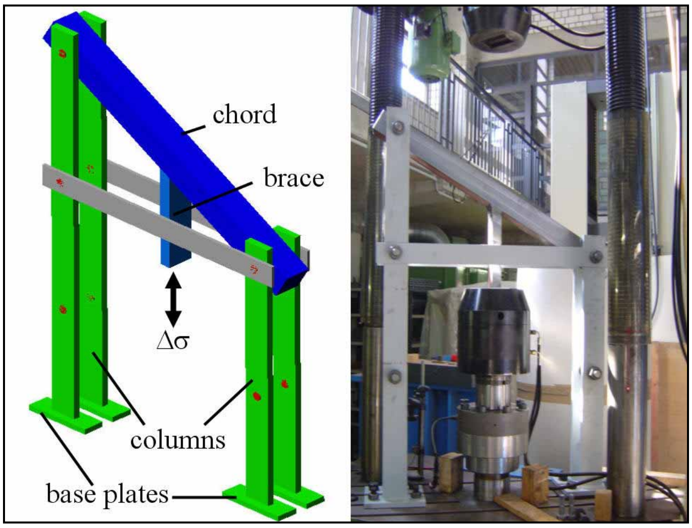

Figure 3. Test setup for Y-joints

The dynamic force loaded at the end of the brace simulated a stress range $\Delta\sigma$. During the tests the dynamic force was measured with a load cell and the deformations were recorded online by inductive displacement transducers. For some test specimens strain gauges were installed additionally to evaluate the local stress state in the near of weld toe and weld root.

2.3 *Post weld treatment by UIT*

Due to the plate thickness effect the fatigue resistance has to be reduced according to offshore-guideline (Germanischer Lloyd 2004). For example the reduced fatigue resistance at the chord is:

$$\sigma_{c,red} = \left(\frac{t_{ref}}{t_c}\right)^{0.25} \cdot \sigma_c = 0.73 \cdot \sigma_c \qquad (1)$$

where t_{ref} = 25 mm as reference plate thickness and σ_c = fatigue resistance at 2 million cycles.

The reduction in fatigue resistance due to thickness effect (e.g. for the chord thickness 27 %) has to be considered in design studies, which is mostly limiting for the dimensions of tubular joints for offshore structures.

But the fatigue resistance of welded joints can be enhanced by post weld treatment. One method for this is Ultrasonic Impact Treatment (UIT). It is a proprietary technology developed originally in the Soviet Union for use on naval ships to reduce welding stresses (Statnikov et al. 1977). The equipment comprises a handheld tool and an electronic control box (Fig. 4). The tool is easy to handle during application. It operates at the head movement with a mechanic frequency of 200 Hz overlain by an ultrasonic frequency of 27000 Hz. The noise is negligible compared to other peening devices. Several kinds of heads and pins are available and can be chosen in dependence of the surface condition of the weld details to be treated. The method involves post-weld deformation treatment of weld toe by impacts from single or multiple indenting needles excited at ultrasonic frequency, generating mechanic impulses on the work surface (Statnikov et al. 1997).

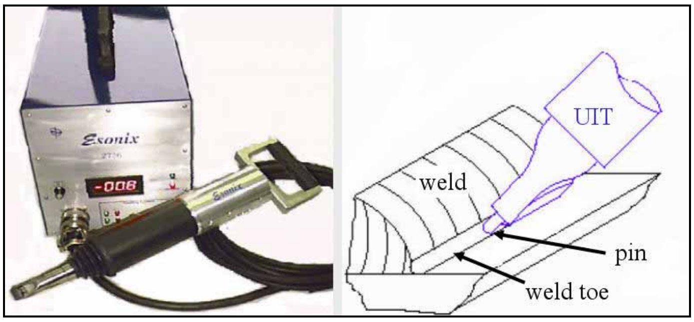

Figure 4. Ultrasonic Impact Treatment (UIT) [Esonix]

The objective of the treatment is to introduce beneficial compressive residual stresses at the weld toe zones and to reduce stress concentration by improving the weld toe profile. Furthermore the area being treated is highly plastically deformed which has the effect of work hardening.

Compared to other impact treatment methods such as air hammer peening, shot peening or needle peening, UIT is claimed to be more efficient involving a complex effect of strain hardening, reduction in weld strain, relaxation in residual stresses reduction in stress concentration and thereby achieving a deeper cold worked metal layer (Statnikov et al. 1997).

2.4 *Test program*

The test program comprises two test series on Y-joints with and without post weld treatment by UIT (Table 3). The first test series without post weld treatment (Y_1 - Y_6) was carried out to get a reference S-N-curve for Y-joints for the as-welded condition. The dynamic loads were recorded as nominal stress ranges $\Delta\sigma_n$ which were varied for the test specimens. The ratio between minimum and maximum stresses was $R = \sigma_{min} / \sigma_{max} = 0.08 - 0.16$ depending on the servo-hydraulic system of the testing machine.

The second test series (Y_7 - Y_12) have been performed with the same procedure like the first test series but additionally with post weld treatment by UIT. The treatment was carried out according to the manufacturer's procedure document (Applied Ultrasonics 2000). The indenter consisted of three 3 mm diameter pins, fitted in a single holder. The treatment was carried out in short multiple passes.

Table 3. Test program

Test series	Test No.	weld toe [-]	$\Delta\sigma_n$ [N/mm²]	R [-]	N [$\cdot 10^6$]
1	Y_1	as welded	28.8	0.13	0.12
	Y_2	as welded	25.6	0.08	0.15
	Y_3	as welded	15.0	0.15	1.10
	Y_4	as welded	19.8	0.13	0.24
	Y_5	as welded	10.2	0.16	3.39
	Y_6	as welded	16.4	0.13	0.45
2	Y_7	UIT	27.1	0.15	0.82
	Y_8	UIT	22.7	0.12	3.75
	Y_9	UIT	34.5	0.12	0.16
	Y_10	UIT	26.1	0.11	0.75
	Y_11	UIT	32.0	0.10	0.18
	Y_12	UIT	28.5	0.10	0.51

3 FATIGUE TEST RESULTS

3.1 *Failure modes*

During the tests fatigue cracks mainly occurred at two positions – at the toe or at the root of the weld. For test specimens without additional fillet welds at the root the crack was always detected at the root because of higher notch effects.

But for tests with additional fillet welds at the root the position of cracks changed to the toe. It can be noticed that welding with additional fillet welds at the root had a great influence on the place where the fatigue crack began. For a good performance of post weld treatment by UIT, it is therefore desirable to match the fatigue crack growth life from root defects to the fatigue life of the treated toe. In this way larger size fillet weld reduced stress concentration adjacent to the weld root, contributing to increased fatigue life. An example for a fatigue crack is shown in Figure 5.

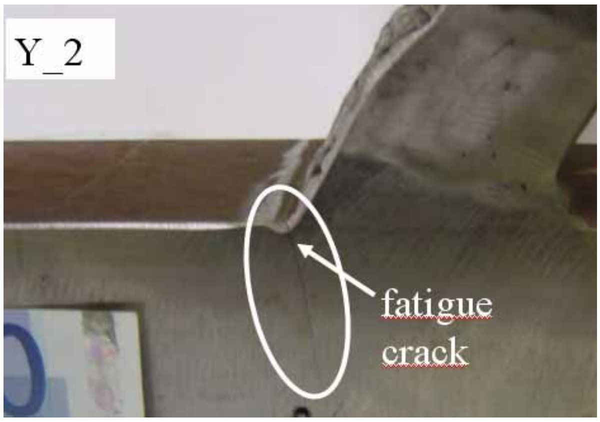

Figure 5. Test specimen Y_2 with fatigue crack at the weld toe

After the fatigue tests several weld details and crack surfaces were cut out from the Y-joints and were examined for origins of fatigue cracks. Figure 6 presents the weld toe of test specimen Y_5 for as welded conditions. In the near of weld toe three zones can be identified: 1. weld metal, 2. heat affected zone and 3. base material. The notch radius of the weld toe is $r_{as\ welded} = 0.4$ mm.

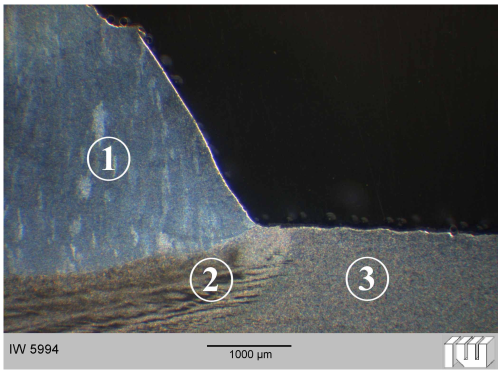

Figure 6. Weld toe of Y_5 (as welded)

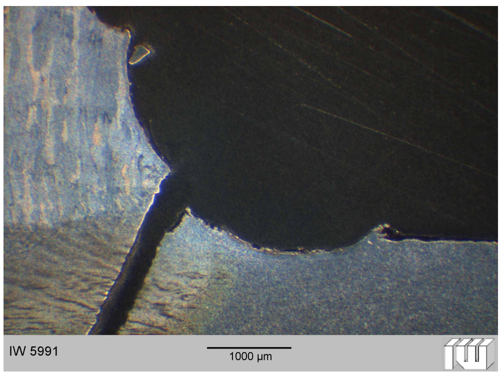

Figure 7. Treated weld toe of Y_9 with fatigue crack (UIT)

Figure 7 shows a photomicrograph of a typically treated weld toe at 50X magnification. Due to the post weld treatment by UIT the surface of the weld toe was highly plastically deformed and the notch was rounded. The weld toe of test specimen Y_9 is shown in Figure 7 after post weld treatment and fatigue testing. Analogous to the test specimen Y_5 in Figure 6 the three zones are visible. The notch radius of the treated weld toe increased to $r_{uit} = 1.8$ mm. Furthermore the fatigue crack can be observed starting from surface between the weld metal and the heat affected zone. Fatigue Cracks in welded joints are often detected at this position because the heat affected zone has a high degree of hardness.

3.2 *S-N curves*

All test results are summarized in two S-N-curves (Fig. 8). The S-N curve of the joints with UIT shows a significant increase in fatigue resistance compared to as welded joints. The as welded joints can be classified in FAT 90. This result corresponds to recommendations for tubular joints according to the offshore-guideline (Germanischer Lloyd 2004) based on the hot-spot-concept.

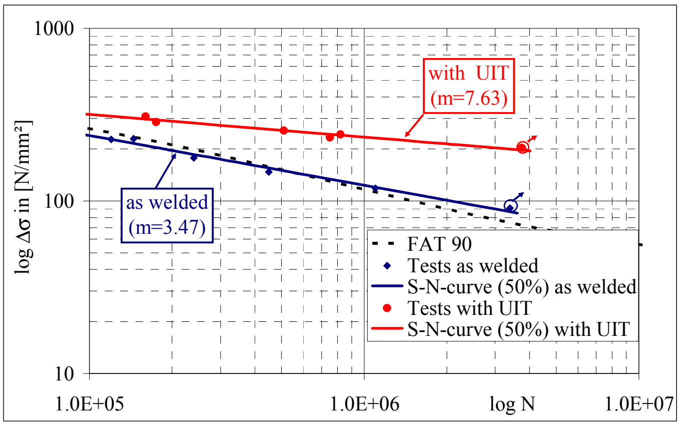

Figure 8. S-N-curves of both test series (as welded and UIT)

With $\Delta\sigma_c = 204.5$ N/mm² for 2 million cycles the fatigue strength after post weld treatment by UIT was double compared to as-welded ($\Delta\sigma_c$ = 95.5 N/mm²). The slope of the first test series with as-welded joints is m = 3.47. This value can be compared to recommendations of design guidelines for fatigue limit state (m = 3 for $N<5\cdot10^6$). But for the second test series with UIT the slope of m = 7.63 is significantly higher. With the experimental results the validity of the thickness effect could be confirmed for a plate thickness of 90 mm. The parameters of both S-N-curves are given in Table 4.

Table 4. Parameters of S-N-curves

Test series	$\Delta\sigma_c$	slope m	N_R for $\Delta\sigma_c = 100$
	[N/mm²]	[-]	[x10^6 cycles]
as welded	95.5	3.47	1.7
UIT	204.5	7.63	475.1

4 NUMERICAL SIMULATIONS OF Y-JOINT

On the first level a 3D-model of the whole test specimen was analyzed using finite element code ANSYS (Fig. 9). This model contained all boundary conditions, but excluded the actual weld notch effects. The weld profile was modeled as a notch having 60° flank angle with a theoretically zero toe radius. With this model the stress concentrations at the weld can be observed using the hot spot concept.

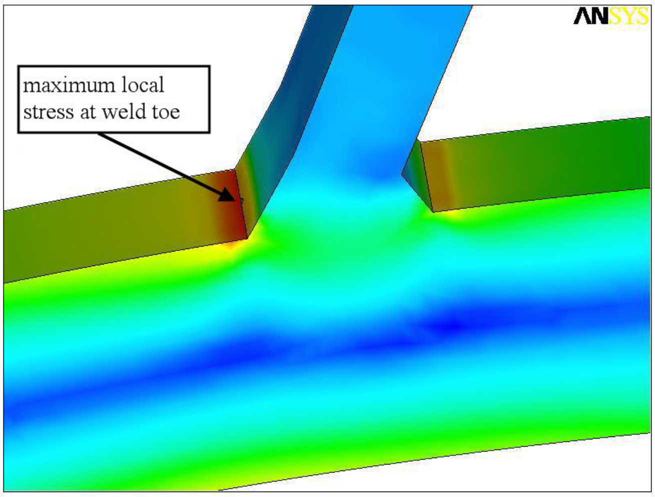

Figure 9. Stress concentrations at toe and root of the weld

The stress concentration factors (SCF) were determined for the toe and root of the weld with the following equation:

$$SCF = \frac{\sigma_S}{\sigma_N} \quad (2)$$

where σ_S = local stress at the hot spot and σ_N = nominal stress at the end of the brace.

To determine the hot spot stress two extrapolation points are necessary. The first point is located at the chord surface in a distance of $0.4\cdot t_C$ from the hot spot the second in a distance of $1.0\cdot t_C$. The calculation is comparable to the calculation of strain concentration factors if the stresses are limited to linear elastic range. The experimental SCF's at the chord were measured with strain gauges in the near of toe and root of the weld. The SCF's derived with numerical simulations are compared to experimental results. The comparison is presented in Table 5. The experimental and numerical SCF's for weld toe and also for weld root show a very good agreement.

Table 5. Comparison of strains and SCF's at the chord

hot spot	method	ε_S (0.4 t_C)	ε_S (1.0 t_C)	SCF
		[µm/m]	[µm/m]	[-]
weld toe	FEM	725	632	6.61
	Experiment	707	614	6.46
weld root	FEM	598	509	5.53
	Experiment	609	524	5.59

Figure 10 shows a curve of the strain path perpendicular to the weld at the chord. The curve was estimated with the FE-model. The stress increases nonlinear near the weld toe. Furthermore, the diagram includes all SCF values measured with strain gauges at the chord for a certain load level. The test results agree very well with the numerical stress curve. So it can be noticed that the stress concentration due to the local geometry of the Y-joint is correctly comprised in the 3D-model.

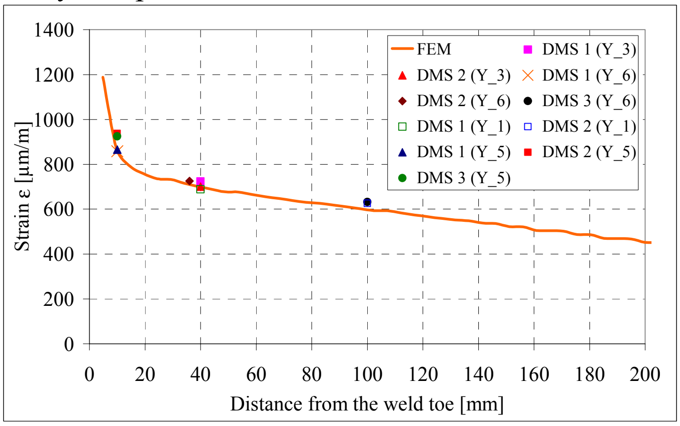

Figure 10. Numerical strain curve perpendicular to the weld in comparison to measured strains

5 COMPARISON BETWEEN WELDED AND CAST JOINTS

5.1 *Geometry of offshore structure (Tripod)*

Welded and cast joints for Tripods are analyzed for the Baltic Sea conditions of the planned wind farm “Kriegers Flak I”. A water depth of 25 m is assumed for a 2 MW turbine. The diameter of the central tube (chord) is $D_C = 4.0$ m and for the braces $D_B = 2.0$ m which are jointed to the chord in an angle of 45°. The objective of the design study is to optimize thicknesses t_C and t_B for fatigue resistance.

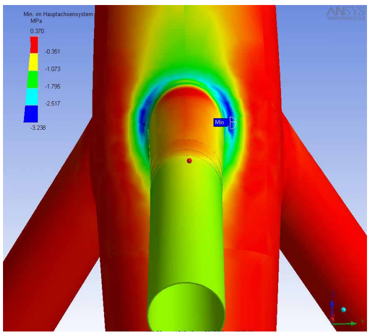
Figure 11. Geometry of tripod and stress concentration

The loads of wind and wave calculated with the deterministic concept are summarized in a rainflow count and load classes. The joints are designed for fatigue limit state with hot-spot-concept. With techniques of sub-modelling the hot-spot-stresses of the joints are calculated, to finally estimate the linear cumulative fatigue damage by Palmgren-Miner. The stress concentration factors for cast joints can be optimized by variable fillet radiuses. Thus, the cumulative fatigue damage for cast joints is decreased and the thicknesses of chord and brace can be reduced significantly compared to welded joints. Weight saving between 20% and 40% are possible for different types of joints for tripods. The consideration of wave spreading allows further reduction for plate thicknesses, but this is possible for both variants. During the fatigue tests a nonlinear lost of stiffness for the joint could be monitored with strain gauges (Schaumann et al. 2006). This has to be taken into account for the dynamic behaviour of support structures.

5.2 *Comparison of fatigue strength*

The experimental results are taken into account in a reanalysis for tubular joints of tripods. In this way the fatigue resistance of welded joints can significantly be increased by post weld treatment with UIT. The estimated value in Table 4 for the treated condition by UIT is higher than fatigue class (FAT) for the unnotched base material thus the maximum fatigue resistance is assumed to $\Delta\sigma_c = 160$ N/mm². The parameter of the fatigue classes for both condition are presented in Table 6:

Table 6. Parameters of S-N-curves

Fatigue classes (FAT)	FAT $\Delta\sigma_c$ [N/mm²]	slope m_1 [-]	slope m_2 [-]	Damage D [-]
as welded	100	3	5	27.2
UIT	160	7	7	1.4

Two effects of UIT cause a better fatigue performance in the treated condition. At first the higher value for $\Delta\sigma_c$ and second the lower slope of the S-N curve. The lower cumulative fatigue damage for the same life time estimated in Table 6 allows weight savings which are comparable with savings by cast iron joints. The optimized thicknesses for different type of joints are compared in Table 7. For welded joints of future offshore wind farms the fatigue design would be more competitive if the effects of post weld treatment by UIT will be considered.

Table 7. Comparison of plate thicknesses

type of joint	upper tripod-joint		lower tripod-joint	
	t_C [mm]	t_B [mm]	t_C [mm]	t_B [mm]
welded without UIT	200	100	120	50
welded with UIT	90	60	80	50
cast iron	90	60	80	50

But for detailed numerical analyses of UIT-effects a sub-model is necessary. Thus, a second level of numerical studies has to be carried out with simulations for a single weld seam including the welding process followed by the UIT-process. This will be part of future research work.

6 CONCLUSIONS

Fatigue tests on welded joints were carried out to estimate the influence of post weld treatment by Ultrasonic Impact Treatment (UIT). This method introduces compressive stresses and plastic deformations at the weld toe reducing residual stresses and stress concentration factors. Because of these effects the fatigue strength increased significantly up to $\Delta\sigma_c = 204.5$ N/mm² compared to as welded condition with $\Delta\sigma_c = 95.5$ N/mm². This result corresponds to recommendations for tubular joints according to actual offshore-guidelines based on the hot-spot-concept. A second effect is observed for the slope of S-N curve which changed from 3.47 to 7.63 due to post weld treatment by UIT.

The experimental results were compared to numerical solutions based on a 3D-model of the whole test specimen using finite element code ANSYS. This model contained all boundary conditions, but excluded the actual weld notch effects. With this model the stress concentration at the weld could be analysed using the hot spot concept. The stress concentrations factors derived in experiments and numerical simulations have a very good agreement for the weld toe and also for the weld root.

Furthermore, different types of tubular joints for offshore structures were investigated numerically to estimate the fatigue limit state for both conditions, as welded and treated by UIT. The stress concentration factor for the treated weld toe geometry was determined numerically using sub-model analysis. Finally a comparison between welded and cast iron joints was carried out in a fatigue design study considering experimental results. The lower cumulative fatigue damage for the treated condition allows weight savings which are comparable with savings by cast iron joints. For welded joints of future offshore wind farms the fatigue design would be more competitive if the effects of post weld treatment by UIT will be considered.

7 ACKNOWLEDGMENTS

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