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IMPROVEMENT OF THE FATIGUE LIFE FOR OFFSHORE WELDED CONNECTIONS

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ABSTRACT

The advantages provided by using high strength structural (HSS) steels for offshore construction might by limited by the fatigue resistance properties of the welded connections. Since fatigue crack propagation characteristics are not significantly different between low and high strength structural steels, the best way to improve the fatigue resistance of welded joints in HSS steels is to introduce a longer initiation period. For this purpose, we developed two complementary procedures: an improved weld procedure, and a global post weld improvement technique.

The overall geometry of the fillet weld is controlled to obtain the best stress flow and the lowest stress concentration in the weld toe region. Furthermore the weld toe run is done at the beginning of the welding. This improved procedure gives smaller global and local stress concentrations. The second step to improve the fatigue resistance of such welded joints is post weld shot peening. Such a technique has the advantage of being a "global treatment", not only localized at the weld toe. The compressive residual stress field induced by shot peening has been studied at the surface of the specimen and in depth. By measuring the initial stress field (prior to fatigue testing) and the redistribution of these residual stresses during fatigue, optimum parameters of shot peening (ALMEN intensity, shot diameter, coverage rate, etc) may be chosen.

Fatigue tests were carried out on 30 mm thick T shape welded joints. Comparative results between as-welded and shot peened specimens show the efficiency of the improved weld procedure and of shot peening in improving the fatigue resistance of welded structures.

KEYWORDS

Fatigue of welded connections, high strength structural steels, post weld improvement technique, crack initiation, residual stresses, shot-peening.

INTRODUCTION

Oil development offshore poses problems which increase yearly in importance.

experience of oil companies with marine structures, especially in the difficult conditions of the North Sea, has led to new guidance in the practical approach of design, construction and inspection of structures regarding the fatigue problem.

Offshore structures have set demands for steels with better and better mechanical properties, especially low temperature toughness in both base metal and welded joints. For safety of the structure, the steel must have high resistance to cold cracking and low welding hardenability. Furthermore economic reasons demand minimization of pre-heating, increase of heat input in welding and avoidance of post weld heating.

Steelmakers have learned how to produce such steels, but the advantages provided by using High Strength Structural (HSS) steels for offshore construction might be limited by the fatigue resistance of the welded connections. It is now well known that for conventional joints, most of the fatigue life corresponds to crack propagation rather than initiation.

Since fatigue crack propagation characterisitics are not significantly different between low and high strength structural steels, the best way to improve the fatigue resistance of welded joints in HSS steels is to introduce a longer initiation period. It is then necessary to eliminate the superficial defects introduced by welding or to annihilate their activity (Haagensen, 1981; Bignonnet, 1983).

It is important to note that in actual offshore welded connections, the potential initiation sites are not only at the weld toe but in the weld toe region.

For this purpose, we developed two complementary procedures: an improved weld procedure, and a global post weld improvement technique.

In this work, we have studied the influence on crack initiation of such improvement procedures. The specimen chosen simulates the hot spot of actual welded connections. Since crack growth in tubular nodes involves stress re-distribution, our specimen obviously cannot simulate the propagation of cracks in actual structures, but it is representative of the crack initiation condition.

MATERIAL AND EXPERIMENTAL PROCEDURES

Material and Specimens

The material used in this study is a quenched and tempered structural steel designated hereafter as E460 (French Standard: AFNOR). The steel, provided in 30 mm thich plate, is quenched after hot rolling by the RAC process and tempered at 690°C for 20 min. Chemical composition of the steel is given in Table 1 and the corresponding mechanical properties in Table 2. Note the good characteristics in the short transverse direction, especially reduction in area.

TABLE 1 Chemical Composition of E460 Steel (wt %)

C	Mn	Si	P	S	Ni	Cr	Nb	Al	N
0.17	1.27	0.34	0.022	0.001	0.022	0.022	0.021	0.068	0.012

TABLE 2 Mechanical Properties of E460 Steel

Orientation and location	Yield strength (MPa)	UTS (MPa)	Elongation (%)	Reduction in area (%)	Charpy V Energy - 40°C (J)
Long (full plate)	570	660	20		100
Long (core)	460	600	26	75	
Short-transverse	460	600	23	70	65

The specimens used for fatigue tests simulate the hot spot region of a tubular connection as circled in Fig. 1. Thus a T-shape welded joint is used with a loading mode which ensures load transfer from the attachment to the plate through the weld as indicated in Fig. 2.

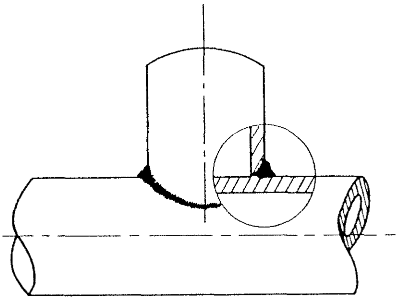

Fig. 1. Hot-spot region to be simulated.

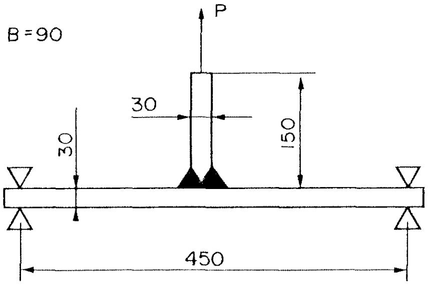

Fig. 2. T-shape welded joint and loading mode. All dimensions in mm.

Welding was done in the vertical-up position on one-meter long plates. Full penetration was assured using an ultrasonic method. From each welded joint, ten T-shape specimens of 90 mm width were saw-cut and machined. The welding parameters are listed in Table 3. The special welding procedure used and the weld geometry are detailed in the next section.

TABLE 3 Welding Parameters for T-Shaped Specimens of E460

Electrode	Position	Pre-heating	I	U	Heat input	Number of runs
E.90.18 D1 ϕ 3.2 mm	Vertical-up (3G)	100°C (flame)	120 A	25 V	20 kJ/cm	35

Residual Stress Measurements

For both as-welded and shot-peened specimens, the residual stresses were determined by X-ray diffraction. Table 4 presents the main experimental characteristics.

TABLE 4 X-Ray Diffraction Conditions

Radiation:	K_α Cr, λ = 2.29 Å, V back filter
Diffraction:	{211} Fe
Ψ_0 angles:	5, 10, 15, 20, 25, 30, 35, 40
Spot size:	1 x 20 mm^2
Detection:	SOLLERS slits

Measurements of both macro- and microstrains through the displacement and the broadening of the diffraction peaks allow the calculation of residual stresses with an accuracy of 35 MPa.

Fatigue Tests and Crack Initiation Detection

Fatigue tests were performed in air on an electro-servo-hydraulic machine. The test frequency was about 10 Hz and the load ratio was R = 0.1. The load was applied with hydraulic grips as shown in Fig. 2. Crack initiation is detected by a potential drop method using alternating current (30 A, 50 Hz). Potential leads are placed every 15 mm along the weld toe. This method allows the detection of 0.1 to 0.3 mm deep cracks.

IMPROVED WELD PROFILE

An improved weld procedure was devised to ensure optimum quality of the welded joints regarding fatigue resistance. The characteristics of this weld presented in Fig. 3 can be summarized in three points: geometrical, practical and metallurgical.

Geometrically, the overall shape of the weld presents as smooth a shape as possible around the toe (see Fig. 3) in order to improve the stress distribution at the weld toe and decrease the global stress concentration factor.
Practically, the weld toe run is performed just after the root runs (see Fig. 3). This allows an accurate position of the weld toe; this run is laid down on the plate without the necessity of following previous runs. Experience has shown that this weld procedure leads to a better weld toe and that risks of geometrical accidents are notably reduced. This weld toe local geometry can be described by the toe angle θ and the toe radius ρ as defined in Fig. 4. The results obtained with 180 measurements from 9 metres of weld, in vertical up position, are given in Table 5, and compared with those of a classical weld.

Metallurgically, the toe run is softened by heat treatments from the filling runs, since the toe run is not the last one. Furthermore, the tensile residual stresses usually encountered at the weld toe are relieved. X-ray stress measurements show the elimination of residual stresses, with the improved weld procedure, at the weld toe.

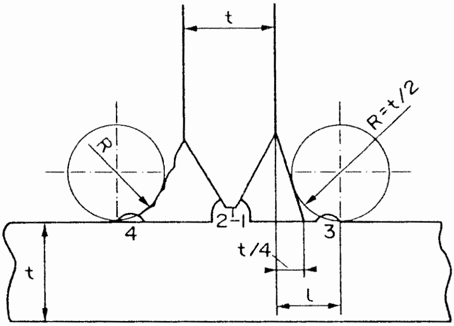

Fig. 3. Weld profile and weld run order.

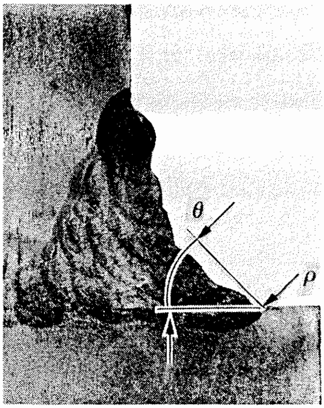

Fig. 4. Local geometric parameters at the weld toe.

TABLE 5 Local Geometrical Parameters

Procedure	Local parameters	Mean	Standard deviation	Mini/maxi
Improved	ρ (mm)	1.7	0.6	0.5/3.2
(180 measurements)	θ (deg)	36	8	17/69
Conventional	ρ (mm)	0.9	0.4	0.4/2
(40 measurements)	θ (deg)	60	12	40/90

Finite element calculations have been performed for idealized profiles, both conventional (weld length $l = t/4$) and improved (Fig. 3). These show (Fig. 5) the better stress distribution of the improved profile, with a stress concentration factor of 1.2 against 1.9 for the conventional one.

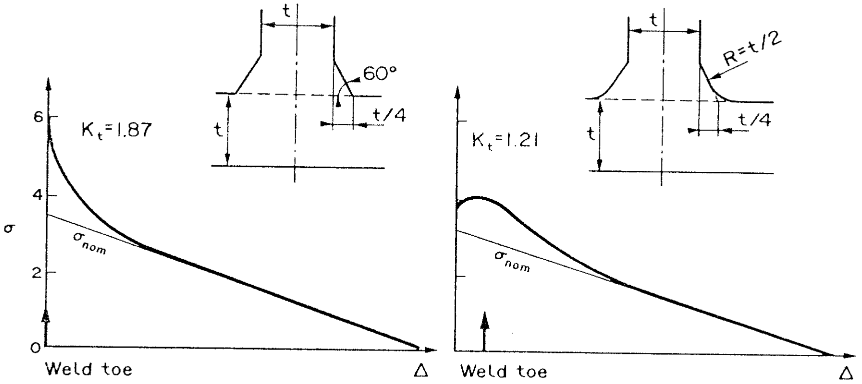

Fig. 5. Stress concentration for conventional and improved weld profiles (Mézière and Proix, 1983).

Such an improved weld procedure provides greatly improved conditions regarding fatigue resistance. Subsequent post-weld treatments which eliminate weld toe defects (grinding, TIG dressing, etc) or introduce compressive residual stresses (shot peening, etc).

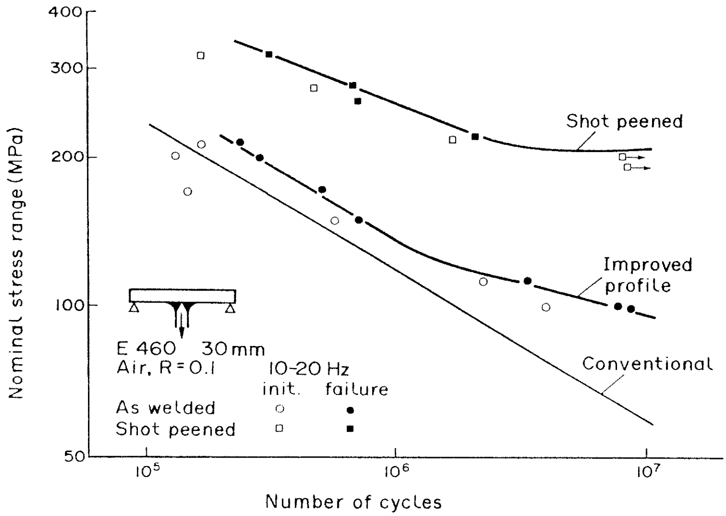

Fig. 6. Effect of the improved weld profile and shot peening on the fatigue resistance of fillet weld.

In Fig. 6, the fatigue results obtained on our specimens made with the improved weld procedure, in as-welded condition, are compared with results obtained by Van Leeuwen, De Back and Vaessen (1981) and Booth (1978) respectively on T-shape (40 mm) and cruciform (25 and 38 mm) joints using a conventional welding procedure. Results are expressed in terms of the extreme fibre nominal stress range at the weld toe.

The better results obtained with the improved weld profile may be attributed to the lower global and local stress concentration, and lower (or absent) residual stresses in the toe region. We should note that the initiation period is rather important: 40 to 50% of the total life.

POST WELD IMPROVEMENT: SHOT PEENING

Choice of Shot-Peening Parameters

To optimize the conditions of shot peening for the improvement of fatigue life, a preliminary study was done. In this study, three different sets of shot peening conditions listed in Table 6 were used on some of the welded T-shape specimens.

TABLE 6 Technological Parameters of Preliminary Shot Peening

Code	Shot size		Almen intensity	Coverage rate (%)
	MIL standard	ϕ mean (mm)		
(1)	MIL 170	0.43	14-16 A	200
(2)	MIL 330	0.84	20-22 A	200
(3)	MIL 550	1.40	8-10 C	200

The distribution of residual stresses induced by shot peening was measured near the weld toe. This was achieved by X-ray diffraction on the surface and in depth after successive electro-polishings. Both displacement and broadening of the diffraction peak were measured to obtain information on residual stresses and microstrains.

The variation with depth of residual stresses and peak broadening are shown in Figs. 7, 8. Shot-peening with parameters of code (1) introduced residual stresses with a maximum of -300 MPa at about 0.15 mm depth. Below 0.25 mm, the stress is below -100 MPa. Shot-peening to codes (2) and (3) (20-22 A and 8-10 C) gave residual stresses of -400 MPa to a depth of 0.45 mm. Diffraction peak broadening measurements confirm that the affected zone is 0.4 to 0.5 mm deep for shot peening (2) and (3) and only about 0.2 mm for shot peening (1) (Fig. 8).

These measurements show that shot peening (1) is less desirable due to its low residual stress level and the small affected depth. Shot peening (2) and (3) gave roughly the same stress distribution. Shot peening (2) (20-22 A, shot MIL 330) was chosen because of its smaller shot size which allows the treatment of smaller defects. The minimum weld toe radius measured in our specimens, 0.5 mm (Table 5), can be treated by the shot size corresponding to condition (2) (ϕmean = 0.84), but the shot size of condition (3) (ϕmean = 1.4) is incompatible with this local geometry.

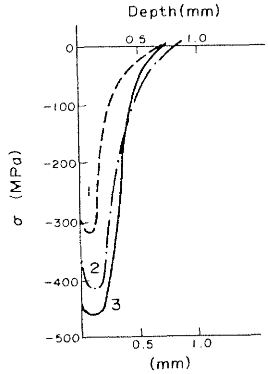

Fig. 7. In-depth distribution of residual stresses induced by shot peening.

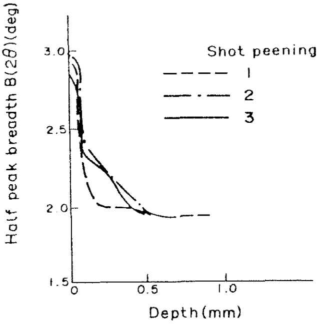

Fig. 8. In-depth distribution of the diffraction peak broadening.

Results

The fatigue lives obtained with the shot-peened specimens (condition (2); 20-22 A, shot: MIL 330) are given in Fig. 6 and compared with the as-welded conditions. The improvement of fatigue lives is remarkable, especially at high cycles. It is important to note that the crack initiation period corresponds roughly to 70% of the total life.

Shot peening, contrary to a simple grinding or TIG dressing, has the advantage of being a "global" improvement technique i.e. which not only improves the weld toe but the overall weld. This is of importance because on an actual structure, the initiation sites in tubular connections are not only at the weld toe but in the weld toe region, i.e. between the two or three runs above the toe. This is also the situation for our improved weld profiles; some of the specimens were broken by cracks initiated at edges of the first or the second run above the weld toe.

CONCLUSIONS

This study shows the improvement in fatigue life provided by an improved weld procedure and shot peening as a global post weld improvement technique.

The characteristics of our improved weld procedure are the following;
- a controlled global geometry with a toe profile following a radius of half of the attachment thickness;
- a weld toe run which is laid down just after the root runs.

Such a weld profile presents several advantages:
- practical: better precision and control in welding toe,
- geometrical: lower global and local stress concentration,
- metallurgical: tensile residual stresses are removed from the weld toe and the toe runs are softened by the subsequent filling runs.

Experimental results show an increase in fatigue life essentially in high cycle fatigue.

Shot peening was studied as a global treatment in order to improve the initiation properties and the fatigue life. The choice of the best technical parameters (Almen intensity and shot size) was based primarily on X-ray measurements of the stress field induced by shot peening: compressive stress intensity and affected depth. As a secondary criterion, shot radius should be smaller than weld toe radius. Results show marked improvement in fatigue life of shot-peened welds, especially in high cycle fatigue.

ACKOWLEDGMENTS

The authors would like to express their gratitude to M. Barrère for technical assistance and to W R Tyson for preparation of this paper and reading the final transcript.

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