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# Repair of Offshore Structures by Underwater Wet Welding Design and Fatigue Assessment

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## Abstract

Under water wet welding is an economically alternative for the repair of offshore structures. In this paper investigations on the fatigue strength of a wet welded pipe structural member have been reported. For the connection a special sleeve patch design has been developed. The joint was fatigue tested. The evaluation of the test was carried out by means of the hot-spot approach with regard to several extrapolation rules of the hot-spot stress. Obtained results have been compared to actual classfication rules and recommendations.

## 1. Introduction

With the increasing age and extended service life the repair of offshore structures requires more and more attention. In this context under water welding plays a key role. The hyperbaric dry welding used today is time-consuming and costly. A more economically alternative would be under water wet welding, which has been intensively developed during recent years. This method is now in stage, where the validation of strength properties may lead to its practical application in strength members, especially those subjected to fatigue load. Topic of an Eurepean Community sponsored project is the provision of fatigue data for underwater wet repaired structural members.

## 2. Design, Welding Performance and Testing Model

The structure investigated consists of two hollow section members connected by an overlapping patch sleeve. With regard to the environmental conditions in under water wet repair welding a newly designed shape of the patch was used. The design is based on some experiences with under wet welding on small scale specimen[1,2]. Figure 1 shows the pipe-patch sleeve connection and the patch design. The overall length of the test specimen is about 1500 *mm*. The pipes in the connection have a diameter of 406 *mm* and a wall thickness of 22 *mm*. The patch sleeve has been fabricated from a 15 *mm* thick plate by flame cutting and rolling to its sleeve form. The longitudinal weld of the sleeve ends was carried out in air.

These design results in a very short distance(about 100 *mm*) which has to be welded in the overhead position. This is important to prevent problems caused by hydrogen susceptibility of

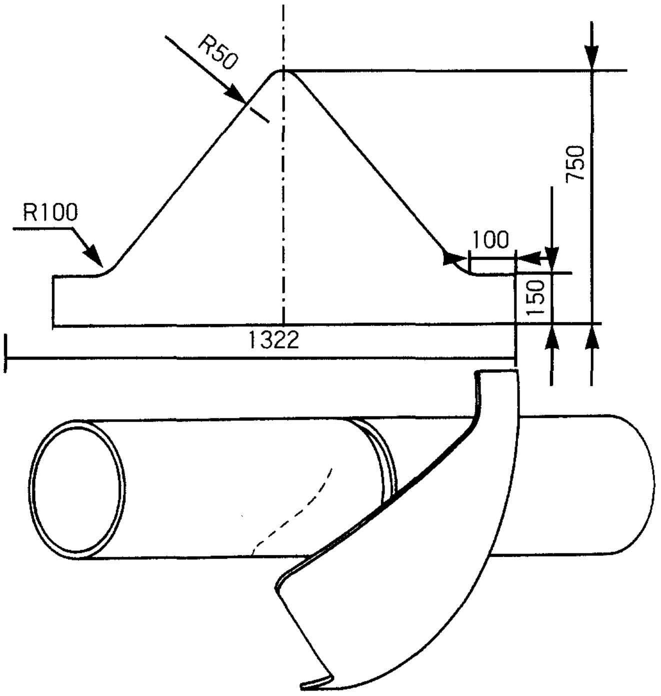

**Figure 1.** Design of the Patch Sleeve

the steel which may yield cold cracking (HICC). As material for the pipes a steel X 52 N Mod. and for the patch a St 52-3N(acc. to DIN 17100 [3]) was selected. these materials are commonly used structural steels in the North Sea area. They show a high carbon equivalent above 0.4%.

**Tablel.** Chemical composition(%)and mechanical properties of the selected materials

| Material | C | Si | Mn | P | S | Al | Cr | Ni | Cu | V | Nb |
|---|---|---|---|---|---|---|---|---|---|---|---|
| St 52-3N | 0.13 | 0.33 | 1.3 | 0.014 | 0.004 | 0.042 | - | - | - | - | - |
| X52N Mod | 0.13 | 0.37 | 1.35 | 0.008 | 0.001 | 0.05 | 0.15 | 0.06 | 0.08 | 0.041 | 0.038 |

|  | Yield Strength $[N/mm^2]$ | Tensile Strenth $[N/mm^2]$ | Elongation [%] | Toughness at 20°C [J] |
|---|---|---|---|---|
| St 52-3 N | 380 | 510 | 28 | 208 |
| X 52 N Mod | 364 | 530 | 32 | 156 |

The following table gives the most important alloy elements and material properties.

The welding was carried out in a diving chamber with fresh water and hand metal arc welding(MAW) in 20 *m* water depth(mwd). In the weld process an electrode commercially used in offshore repair work was employed. Table 2 contains the chemical composition of the weld in 20 mwd.

**Table2.** Chemical composition of the weld material produced in 20*m* water depth (fresh water)

| Alloys[%] in 20 mwd |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| C | Si | Mn | Cu | V | Cr | Mo | Ni |
| 0.09 | 0.20 | 0.28 | 0.05 | 0.012 | 0.01 | <0.01 | 0.04 |

In wet welds higher hardness values and lower ductility generally have to be expected compared to welds produced under atmospheric conditions. The topology of the weld surface is more uneven and the weld properties (exterior state, probability of imperfections, strength) depend on the weld position.

## 3. Full Scale Specimen Test

The investigation of a structural member with complicate shape and complex influences caused by the weld performances can best be done by full scale specimen testing. Thus, scale effects will be prevented in the transmission of the results to real constructions. Further, a comparison with existing recommendations is easier. That' s why for the test specimen a pipe diameter of 406 *mm* was chosen.

### 3.1 Scope of the Test

Tasks of the full scale specimen test are the determination of the member stressing and of the fatigue performances. Therefore strain gauge measurements at the specimen were necessary. For comparative theoretical investigations of the stress state the method of Finite Elements(FEM) is an appropriate mean. The fatigue test will ve evaluted according to modern approaches of fatigue assessment. Result of this assessment procedures will be compared with classification rules and recommended guidelines.

Because of only one available specimen a statistical evaluation can not be carried out. However, a comparison of the test result with design curves and recommendations gives an identification for fatigue properties of this connection. The comparison will be carried out under the usual assumption that the result is located near the lower bound of scatter band.

Because of the difficulties of the welding process the overhead welded position can be assumed to be of most interest with regard to crack initiation.

### 3.2 Testing Arrangement and Duration

The test was carried out in the large strength testing facility of the Institute for Naval Architecture(IfS). To mount the pipe model into the facility the test specimen was lengthened to about 6000*mm*. For this, two extension pipes were orbital welded to the specimen.

The test pipe hung up horizontally in a portal. The ends of the pipe were mounted in bearings which admitted no bending moment to the facility. The model was loaded by two 1000*kN* hydraulic cylinders. The load was transmitted over jack cover plates and special webs. Figure 2 shows the test arrangement. Thus, the model is loaded in 4-point-bending. Its middle section with the repair joint is stressde by constant bending moment.

The fatigue test was carried out under constant amplitude load in air, load controlled with sinusoidal progress and a testing frequency of about 0.3 *Hz*. The upper load per hydraulic jack was 150 *kN*, the lower load 10 *kN*. This relative low load range was chosen to obtain crack initiation in the high cycle range. With regard to collapse problems the jacks were equipped with a way limit switch.

On the specimen a large number of strain gauges(about 100) was applied. The strain gauge measurements were used to find out the global and local(notch of geometric) strains and to control the running test. The overhead welded position was situated in the maximum tension fibre of the pipe. Therefore, this position was stressed due to pure zero-to-tension load (stress ratio R=0).

The crack had to be expected in this area perpendicular to the pipe surface at the weld toe.

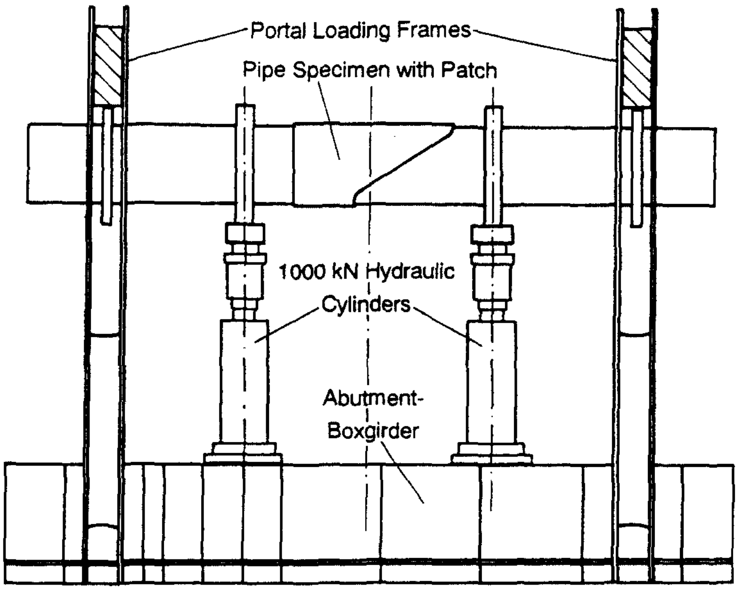

**Figure 2.** The arrangement of fatigue testing

The crack initiation was controlled by strain gauge measurements. These measurements were carried out after an appropriate number of cycles. Additionally the crack initiation and its growth was observed using colour penetration method.

The test was stopped when a technical crack i.e. a crack which could be found with usual observing techniques and in service conditions had developed.

## 3.3 Strain Gauge Measurements and Finite Element Calculation

For the accompanying strain measurements uniaxial (single/chains) and biaxial (crosses/rosettes) gauges were used. Thus, at the several specimen areas uniaxial and biaxial strains have been measured. For comparison with FE calculation the uniaxial and principal stresses at the pipe surface were calculated. All strains have been measured as strain ranges between lower and upper load.

Because of testing of only one specimen a statistical evaluation of the measured strain values was not possible. Consequently, differences in pipe wall thickness could not be detected and equalised. However the nominal stress/strain estimated by means of the elementary beam bending theory differs from measured values by less than 5%(10% tolerances in wall thickness are permitted acc. to DIN 17172[3]).

A nominal stress range of about 83 $N/mm^2$ was measured at the fiber of maximum tension stress remote from the weld toe.

For theoretical stress evaluation calculations by means of the Finite Element Methods were carried out. The larger part of the specimen was modelled with 20-node isoparametric brick elements. Figure 3 shows the FE mesh.

Thus, incompatibilities between element classes and transition problems could be avoided in the middle part of the mesh. At the ends the pipe was modelled with beam elements constraint to the brick elements.

Because of symmetry only a half specimen had to be modelled. Weld reinforcement has been

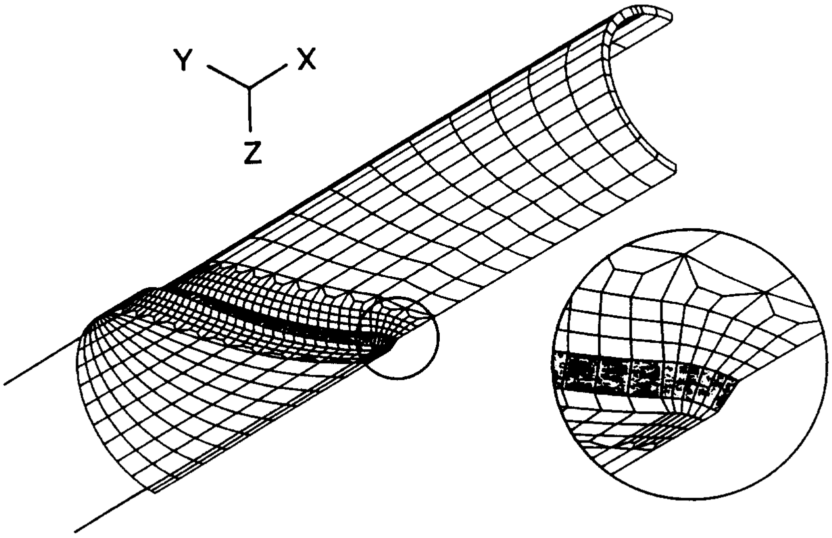

**Figure 3.** Finite element mesh of pipe and patch

shaped according to castings taking from the original weld. Transition radii and discontinuities were not considered.

In front of the overhead position weld the brick elements were covered with very thin membrane elements to calculate the stress distribution directly at the surface.

At the toe of overhead position weld three elements were modelled with a length equal to the pipe wall thickness. Thus, the hot-spot extrapolation rule according to [4] could be used.

To prevent penetration of pipe and patch sleeve due to load the gap was filled with gap trusses. Hence, the contact between the members was simulated frictionless. The calculation model was loaded in the same manner as the specimen but with the range of 140*kN* as static load. The results of calculation represent the ranges of stresses and strains due to load range in the experiment.

## 3.4 Comparison of Measurement and Calculation Results

Figure 4 shows a comparison of measured stresses before the toe of the overhead position weld and the equivalent FE-calculated.

Both stresses do not differ more than 5-6%. That is in good agreement with regard to the integral behaviour of the strain gauges and a possible thickness tolerance of the pipe wall up to 10%. All measured strains and stresses are slightly lower than the calculated ones. This may be due to the above mentioned intefration effect of the strain gauge measurements. Thus the calculation model is validated by the strain gauge measurements and its results can be used for further investigations.

As described above (see figure 4) the crack initiation has to be expected at the toe of the overhead position weld. A tensile stress field with a main principal stress in pipe longitudinal direction was found in this point. This stress is the driving force for crack initiation and propagation. It is useful to employ this stress for fatigue evaluation.

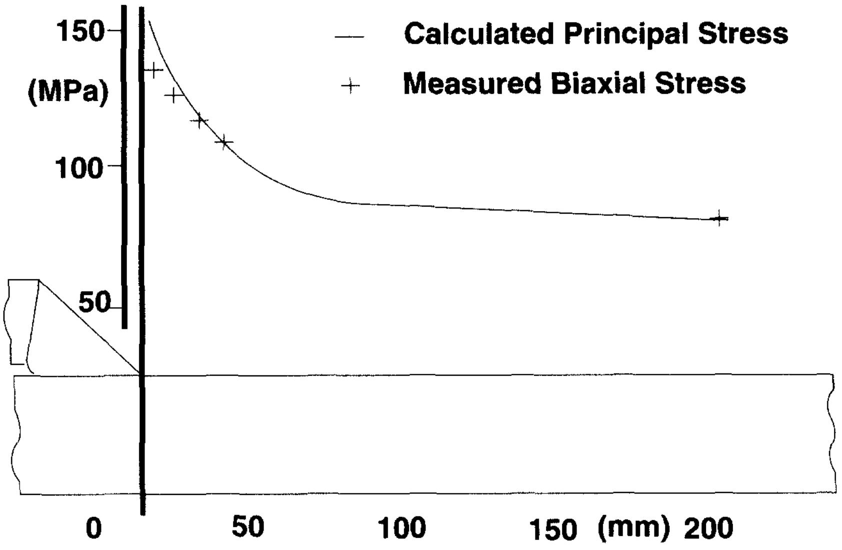

**Figure 4.** Comparison of measured and calculated Stresses

## 3.5 Test Results and Evaluation

The first crack was detected by means of a pocket-leans after 1.2 · $10^6$ cycles. After 1.4 · $10^6$ cycles the test had to be stopped because of failures in air welded seams. The final crack length was about 20 *mm* and the crack could be observed by eyes under load. The whole testing time was about 17 weeks.

After cutting the patch with the crack into segments, another crack was found starting from the weld root. This crack occured due to shear stresses in the weld between patch and pipe. This damage will not be further considered because of a lack of information. The gap between pipe and patch was less than 0.3 *mm* thick at the overhead position.

An appropriate method to estimate the fatigue life of hollow section joints is the hot-spot approach. In this concept the stress concentration due to the geometric notch of the joint is considered without influences of the weld itself. Measured or calculated maximum stresses have to be extrapolated to the weld toe (hot-spot). The hot-spot stress evaluation will usually be carried out by means of linear or quadratic extrapolation rules.

Aim of this investigation was the application of the hot-spot approach for the repair welded hollow pipe member. Three extrapolation rules were employed. The obrained hot-spot stress ranges were compared to actual design curves given in classification rules or recommendations.

Using a linear extrapolation of the main principal stress range by means of an empirical chosen line according to [5] a hot-spot stress range of $\Delta\sigma$=130.0 $N/mm^2$ was found.

Another well known rule according to [6,7] is the linear extrapolation through two support points situated 0.4t and 1.0t (t=pipe wall thickness) in front of the weld toe. The evaluated hot-spot stress range from the main principal stresses amounts to $\Delta\sigma_{HS}$=147.9 $N/mm^2$.

The third extrapolation rule according to [4] base on a quadratic extrapolation of the stress calculated by Finite Elements. Three elements in front of the weld toe at the overhead position were modelled with a width equal to their height (=pipe wall thickness). The results obtained in the integration points of the elements have to be re-evaluated to the upper element bound. Thus, three element stresses(main principal stresses) at the pipe surface were provided to support the extrapolation parabola. Using this method $\Delta\sigma_{HS}=159.6$ *N/mm²* were obtained.

The three hot-spot stress ranges could be compared with design curves. The following figure 5 shows the calculated values in comparison to four actual design curves. The attached table contains the equations for these lines for 97.5% probability of survival beyond their break points.

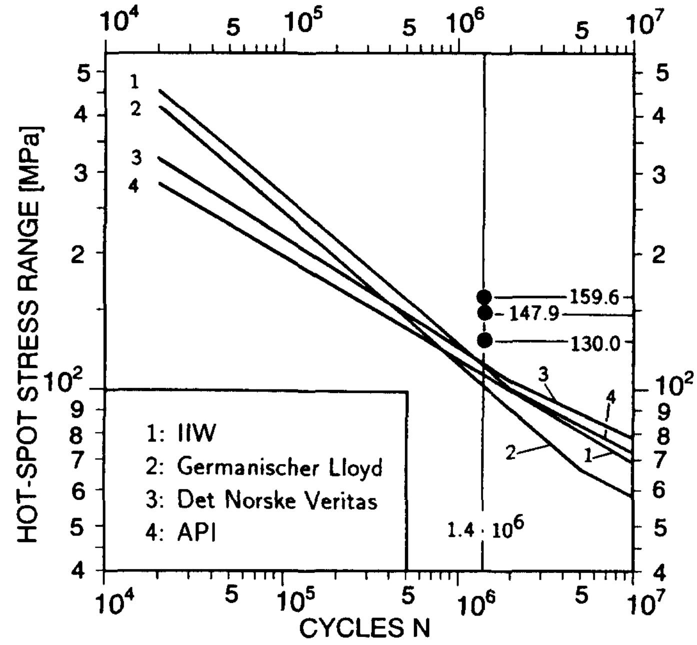

**Figure 5.** Test result compared to actual design curves

**Table 3.** Hot-spot stress range design curve

| Hot-Spot Design Curves $\log N = C - m \cdot \log \Delta\sigma_{HS}$ | | | | |
|---|---|---|---|---|
| Code | C<br>[-] | m<br>[-] | Reference Value $\Delta\sigma_R / N = 2 \cdot 10^6$<br>$[N/mm^2]$ | Probability of Survival $P_{\ddot{U}}$<br>[%] |
| IIW[5] | 12.571 | 3.0 | 100 | 97.5 |
| DnV[7] | 14.57 | 4.1 | 104 | 97.5 |
| GL[8] | 12.164 | 3.0 | 100 | 97.5 |
| API[9] | 15.06 | 4.38 | 100 | 97.5 |

As figure 5 shows the fatigue strength of the structural member may be slightly underestimated by the design curves if the usual scatter of fatigue life' s is assumed. The design curves considered give a more or less conservative estimate of the stress range at $1.4 \cdot 10^6$ cycles.

Additionally the results were evaluated according to the design curves given in [5]. This gives the possibility to estimate the influence of the pipe wall thickness. Further, this recommendation gives the belonging nominal stress design curve. Both curves are valid for 97.5 % proba-

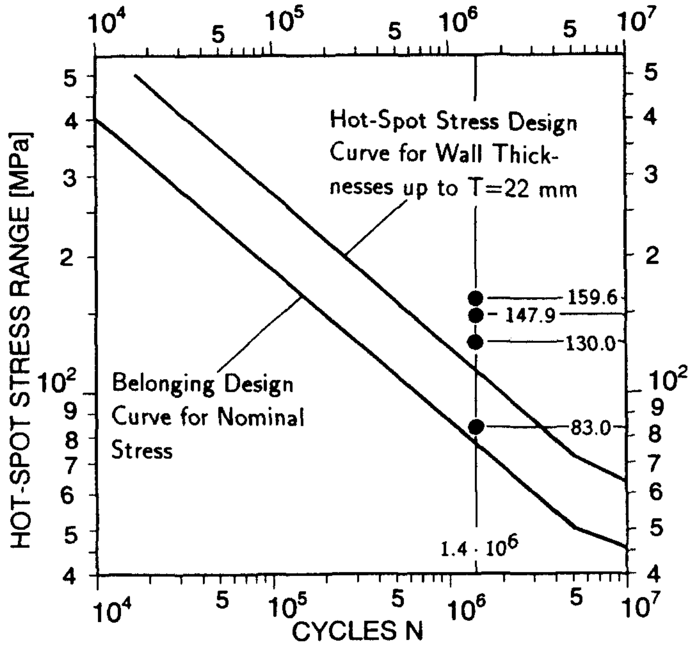

**Figure 6.** Test result and hot-spot stress range design curve with consideration of the wall thickness and nominal stress range

bility of survival. If available, the nominal stress can be considered. Figure 6 shows the three evaluated hot-spot stress ranges and the nominal stress range $\Delta\sigma_N = 83\ N/mm^2$ in comparison to these design curves. As described above, the design curves describe the fatigue life slightly conservative. The same yields for the nominal stress curve.

From the figure 6 it could be assumed that the hot-spot stress range is slightly overestimated by the quadratic extrapolation.

## 4. Summary and Conclusions

Under water wet welding has been employed to connect pipe structural members. A newly designed sleeve patch was applied in the joint. The connection was fatigue tested. The test was carried out in 4-point-bending under constant amplitude load in air. The especially interesting overhead welded position was stressed under pure zero-to-tension.

Stress state and crack initiation were controlled by strain gauge measurements. As expected a crack in front of the overhead position weld has developed. The fatigue test was stopped after $1.4 \times 10^6$ cycles. The crack length amounted to about 20 *mm* which can be considered as a technical crack.

The test was evaluated according to the hot-spot approach. Theoretical investigations of the model were carried out by means of the Finite Element Method. The calculation showed a good agreement to strain gauge measurement. Thus, calculated stresses were employed for the hot-spot investigation.

Three extrapolation rules for the hot-spot stress were applied. The results were compared to actual hot-spot design curves. The stress range for the fatigue life obtained from the test could be predicted by means of the hot-spot approach. Assuming an usual scatter of fatigue life' s the design curves may slightly underestimate the fatigue strength of the structural member.

It has thus been shown that the hot-spot stress approach is applicable with sufficient accuracy for this type of repair investigated. The fatigue strength of the under water wet welding is shown to be equivalent to an atmospheric weld.

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