Adoption of Ultrasonic Impact Treatment - Design of Steel Structures with Enhanced Fatigue life

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Abstract The latest stand in technology shows that fatigue strength of steels used for weld constructions is independent of its yield stress point. This is to be regarded as one of the main reasons for the yet delayed implementation of high strength steels in constructions under dynamic loading. Through the implementation of **Post Weld Treatments**, industry has a mean to enhance fatigue strength, particularly in these higher strength steels. Ultrasonic Impact Treatment (UIT) is accepted as a proven Post Weld Treatment in **Maintenance & Renewal**. However due to the fact that applicable Codes & Standards are still under development, UIT has not been generally accepted by the designer of **new steel structures**. This paper offers the designer the first basis for acceptance and approval of UIT as Post weld Treatment.

1 INTRODUCTION

Technologies to enhance fatigue life of welded joints are gaining increasing importance in many areas of steel construction, particularly for its use in high strength steels. A relative new Post Weld Treatment technology that is rapidly gaining market share in the maintenance & renewal market is Esonix® UIT. UIT harnesses and introduces the energy of ultrasound into metallurgy through surface impulse contact. This energy is introduced into the metal by converting the resonant / harmonic oscillations of an acoustically tuned body to mechanical impulses on a surface. The process changes the stress profile and geometric discontinuity at the weld toe. The treatment is particularly marked through its significant fatigue improvement factor, ease of use and high level of repeatability. The offshore, petrochemical, crane and bridge industry already have adopted the benefits of extending fatigue life and rehabilitation of structures by UIT.

Still this technology is rather uncommon by the design engineer and in the construction market of new structures. With UIT as proven technology, the engineer is offered a choice to design a weld detail with FAT Class 80 or the similar weld detail with UIT, obtaining FAT Class 125. With the latter s/he can make use of an enhancement of fatigue by a post Weld Improvement Factor of ≤8 or increase the allowable stress by a Post Weld Improvement Factor of ≤2. The choice of UIT offers the client a reduced CapEx, Capital Expenditure and OpEx, Operational Expenditure, due to a reduction of down time, material saving and enhancement of fatigue life.

2 METHODS OF WELD IMPROVEMENT

With an increase of strength, the fatigue strength of structural steel also increases, whereas this statement is only applicable in this form for ideal (i.e. polished) samples of the basic material. Every imperfection, such as geometrical changes through notches or drill holes, surface faults or even the, in steel construction unavoidable weld, reduces the reliability of high strength steels within reason, which in extreme cases can be equal to the level of strength of normal strength steels.

Still today, Eurocode 3 Part 1.9 recognises fatigue, so as proof of strength being independent of type of steel, and so being independent from number of cycles, construction detail and type of stress ratio R. There has therefore been ongoing effort in improving the fatigue strength of welded joints, through various Post Weld Treatments. Figure 1 shows a rough outline of the various Post Weld Treatment methods of today, whereby they can be subdivided into two main groups:

1. Improvement of weld geometry,
2. Internal stress reduction through alteration in the stress profile.

UIT brings the best of both methodologies together. It improves the weld geometry and introduces compressive stress. Research data related to fatigue of welded steel structures proof that UIT is the most efficient and economical technology for enhancing the properties of steel, compared with other technologies, such as burr grinding, shot peening, Post Weld Heat Treatment and TIG dressing. The track record of UIT includes a number of applications for various industries, such as e.g. bridge construction, offshore installations, the construction of cranes, aerospace, automobiles, power stations and railways. More specific applications are creep, the reduction of weld distortion and the repair of boilers and vessels, especially where Post Weld Heat Treatment is difficult to achieve or uneconomical.

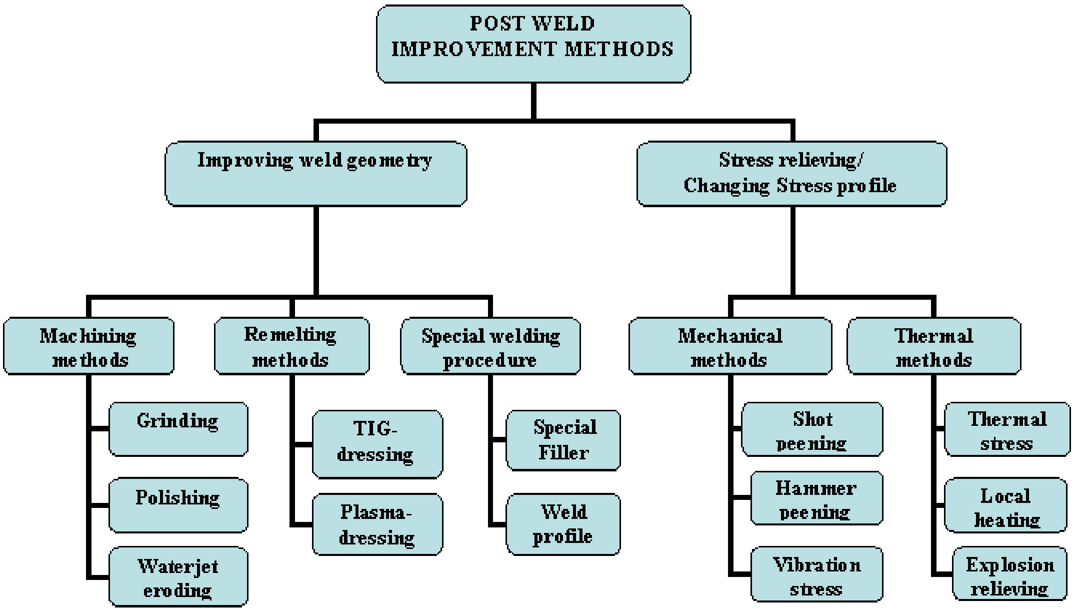


Figure 1: The different Post Weld Improvement Methods

3 INTRODUCING ULTRASONIC IMPACT TREATMENT

3.1 The history of Esonix UIT

Ultrasonic Impact Technology was developed in 1972 and has, since then, been perfected by a team of Russian scientists under the directorship of Dr. Efim Statnikov, for use within shipbuilding, submarine manufacturing and aerospace industries. In 1997, Esonix®UIT technology found its way to a group of businessmen in Birmingham, Alabama. Having an extensive background in the steel, engineering and manufacturing industries, they immediately recognised the significant benefits and potential of this technology. They acquired all its rights and patents and founded the company, Applied Ultrasonics. The core UIT was commercialised across the globe by establishing partnerships with Nippon Steel Corporation for Asia and VolkerWessels for Europe.

3.2 The principle of UIT

The effect that can be obtained from UIT is that material properties are improved by thermo-acoustic mechanical impulses. These impulses are initiated by a 27kHz pulse generator with a power of 1,5 kW. Through a transducer and hardened pins electric pulses are transformed into mechancial pulses. The pins start to resonate and hit the surface of the piece of metal with a mechanical frequence of approximatelly 200 Hz. The impact causes an effective plastic deformation and introduces ultrasonic vibrations and ultrasonic stress waves.

The mechanical impact of the ultrasonic treatment physically improves the geometry of the toe of the weld. The impact introduces a compressive stress and the ultrasonic vibrations and stress waves initiate a stress relaxation: both change the residual stress profile. Figure 4 and tabel I show which effect can be obtained and until which depths[1].

Figure 2: UIT Hand Held System

Figure 3: Treatment of a weld

Improvement of the geometry of the weld toe and improvement of the residual stress profile provide the user with 4 significant benefits:

1. fatigue enhancement by a factor ≤8,
2. material saving by 20 to 40%,
3. reduction of deformation,
4. alternative to Post Weld Heat Treatment.

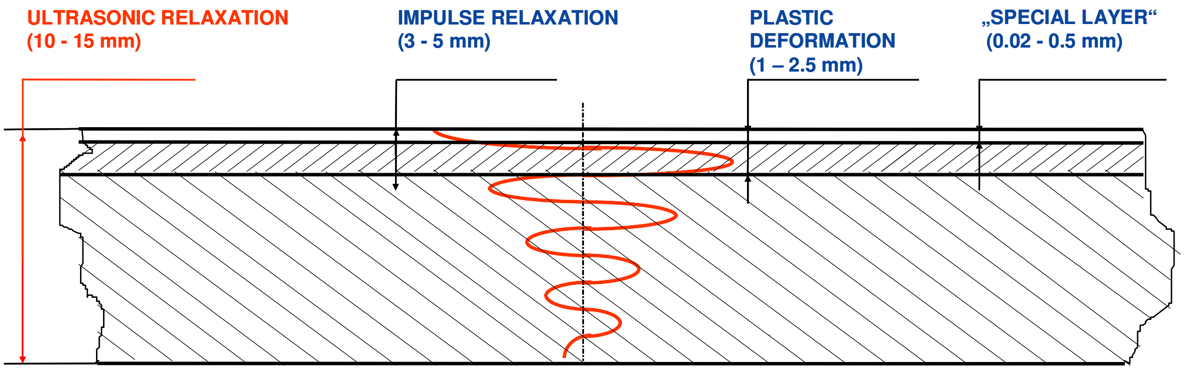


Figure 4 Cut away key of a treated sample

Zone	Characteristics
“White layer”	Increase in resistance to abrasion, corrosion and surface lubricity
Plastic deformation	Increase in fatigue life, compensation for weld deformation, decrease in corrosion fatigue
Impulse relaxation	Decrease of residual stress and strain as high as 70% of the initial state
Ultrasonic relaxation	Decrease of residual stress and strain as high as 50% of the initial state

Tabel I Zone and characteristics of treated steel

4 INTERNATIONAL RESEARCH: SCIENTIFIC BACK-UP FOR FATIGUE ENHANCEMENT

4.1 Prof. Dr. John Fisher of the Technical University of Lehigh, USA

Immediately after Applied Ultrasonics was founded in 1998, an extensive UIT research programme began under the supervision of Professor John Fisher. The programme tested the enhancement of fatigue performance of weld joints by UIT with large-scale rolled beam and built-up specimens with yield strengths of between 345 and 760 MPA. The samples were manufactured by two different international steel manufacturers, Swedish Steel and Nippon Steel Corporation. The programme covered areas of new welded girders, as well as repair procedures and fatigue improvement techniques. The results are recommendations for the AASHTO Design Code of the FHWA (an American *equivalent* to the Eurocode 3 for bridges) to be considered in the design and manufacture of new bridge members, as well as specific field applications for rehabilitation of bridges currently in use. It has been demonstrated that through the use of UIT, Category E weld details achieve Category C or higher fatigue strength [2].

As Welded Detail Category	**Esonix UIT Detail**	
	Stress Ratio	**Enhanced Category**
C’	$R \leq 0{,}5$	B
E’	$0 \leq R \leq 0{,}1$	B
E’	$0{,}1 \leq R \leq 0{,}5$	C’

Table II**:** AASHTO code; recommendations for enhancement of design

Parallel to the test program, John Fisher, Applied Ultrasonics and FHWA began a rehabilitation programme for four bridges on Interstate 66, USA. All four bridges were built in 1979 and had fatigue cracks located at the end of the fillet welds, varying from 8 to 35 cracks per bridge. The bridges were repaired and treated with UIT and monitored through an FHWA inspection regime. No cracks occurred ever since.

4.2 Prof. Dr. Ulrike Kuhlmann of the Technical University of Stuttgart, Germany

4.2.1 S-N curves of various types of steel and stress ratios (R)

In the Fosta Research project 'Efficient Steel Construction of High Strength Steels under Fatigue Load', the University of Stuttgart together with the Weimar' Bauhaus University, the usage and efficiency of the Post Weld Treatment UIT was put under research, as well as its already well-known procedure of TIG Dressing of a typical construction detail, the cross stiffness plate of a girder. For this, fatigue tests were carried out on small and large scale specimens as well as on girders made by the steel types S355, S460 and S690. For better comparability additional test specimens were tested in the "as welded" and shot-blasted condition after welding. With all UIT treated samples of S690 the cracks always started in the base metal and not in the weld toe. With samples made of S355 and S460, the cracks of the UIT treated samples started also at the weld toe, but on a 10 times higher level of the lifetime. Figure 6 shows the applicable S-N curve of 3 types of HHS and a stress ratio of R = 0.1. [3]

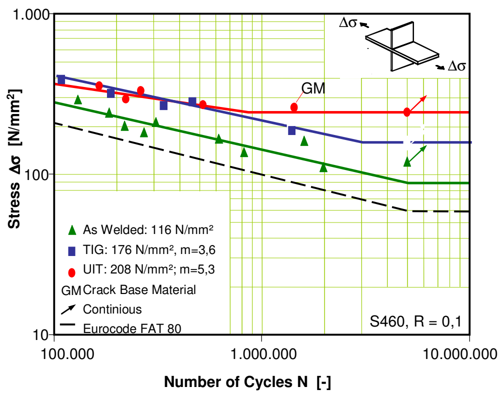


Figure 5: S-N curve S460, TIG & UIT

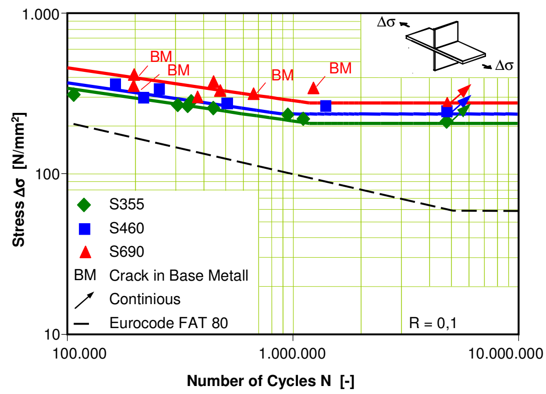


Figure 6: S-N curve for S355, S460 and S690, R = 0.1

From Figure 5 one can see that with the material S460, a stress of 116 N/mm² can be raised up to 208 N/mm² when using UIT with a stress cycle number of $2x10^6$. These differential results show that an increase in fatigue strength can be achieved at up to 120%. This figure indicates the influence of the fatigue strength of the base material. The results show a significant improvement of the UIT effect with a rising yield point. This is due to the fact that with higher yield points, higher internal stresses can be implemented. Practically all the samples using the material S690 had cracks in their basis material. Figure 7 illustrates the endurance of the material S355 using a stress ratio of R = -1 from different tests at the Polytechnic of Esslingen, Germany., also a cross stiffness plate specimen. Remarkable is the reduced spread in results after UIT treatment.

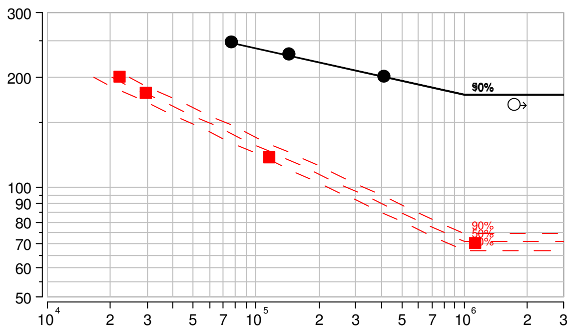


Figure 7: S-N curve S355, R=-1

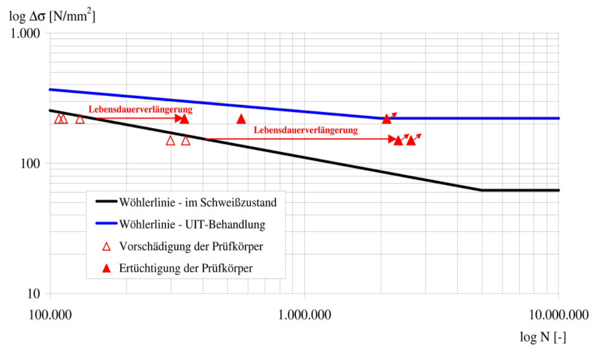


Figure 8**:** Rehabilitation of fatigue life S460, R = 0.1

4.2.2 Rehabilitation of steel structures

It is, of course, also obvious that a Post Weld Treatment should be carried out during the usage period of a welded construction in order to increase the residual life time. For this reason, fatigue tests were carried out on pre-loaded specimens. The specimens were tested in the "as welded" condition up to 80 - 90% of their calculated number of cycles. Then tests were stopped and UIT treated. After UIT treatment the fatigue tests were then continued. Results of a dissertation written at the University of Stuttgart, illustrated in figure 8, shows that the implementation of a UIT process after preloading is also very successful to increase the lifetime of existing constructions. Through a consequent UIT treatment, residual lifetime can reach at least 15 times those of life-time without Post Weld Treatment. Further tests at the University of Braunschweig even determined that the number of stress cycles achieve nearly the same level as the samples achieved in their UIT treated condition at the begin of the tests.

4.3 Prof. Dr. Peter Schaumann of the University of Hannover, Germany

To encourage the economy of steel constructions in the offshore wind mill industry through improved fatigue strength, the efficiency of UIT was investigated on a pipe joint of a foundation structure, made up of S355 (see Figure 9). The welding detail chosen was the junction of a Y-Joint for a tripod foundation of a 2 MW wind mill, type Kriegers Flak (Baltic Sea). This program was done in cooperation with the project 'Experimental and Numerical Investigations of Y-joints for Offshore Structures' by the Institute of Steel Construction at Hannover University [4]. Each notch model consists of a chord (G) and brace (S), which is welded to the chord at a gradient of 60° using an HV weld.

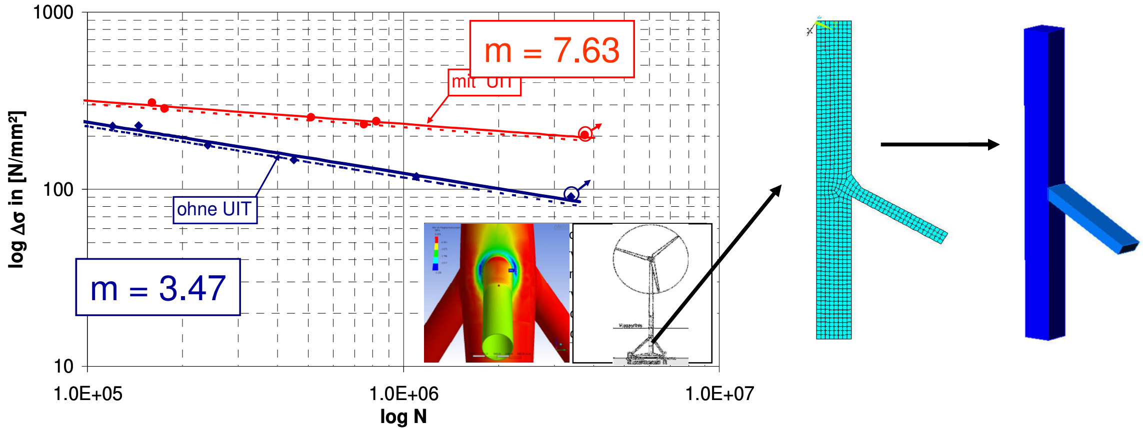


Figure 9: Y-joint with original design and geometry of the test sample and S-N curve

The S-N curves show that through UIT, a significant improvement in fatigue strength of the welds can be obtained. A statistical analysis indicated that specimens without UIT could be classified as FAT Class 90. This result correlates to the classification for pipe joints according to Germanischer Lloyd regulations [5] on the basis of its structural stress concept. In comparison to the first tests, the value of the second, following UIT treated – where $\Delta\sigma_C = 204{,}5$ N/mm² - was twice as high. The value would also lie above the highest FAT Class, which is indicated as 160 for the base material. This means that in this case a fatigue crack could also occur at first in the base material, if there would exist high stress concentration. This was already established in the above mentioned research project 'Efficient Steel Construction of High Strength Steels under Fatigue Stress' from Stuttgart University [5]. Above all, all of the samples of the higher strength material S 690QL were broken in the base material. In this case, applying the higher FAT Class will result in a 16% material saving per tripot which is equal to 55 tons of steel.

4.4 Prof. Dr. Thomas Ummenhofer, University of Braunschweig, Germany

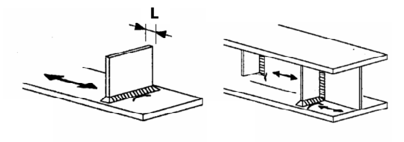
The University of Braunschweig runs an R&D program named REFRESH – extension of life-span of existing and newly welded structures. The objective of this program is, to have determined the new calculation rules for Eurocode 3, part 1.9 by 2009. Included in the programme is an extensive testing program of more than 80 test samples of S355 and S690, fillet and butt welds and production parameters. The programme is running and on schedule. [6].

5 DESIGN AND THIRD PARTY APPROVAL

5.1 Design process for fatigue

Today, the calculation and design of steel buildings is determined in Eurocode 3 (Design of Steel Structures, Part 1-9: Fatigue). Here, the parameters for fatigue stress as well as the identification of stress cycles are laid down. This norm contains methods of proof for determining fatigue strength of building parts under fatigue stress. These methods of proof are based upon results for fatigue tests carried out with test specimens of geometric structural imperfections, similar to such steel components, and originate from the production of steel and manufacturing of parts. The FAT Class illustrates the reference value of fatigue strength in N/mm². In the Code, various construction details are then sub-divided into their corresponding FAT Class.

Table III shows the construction detail ‘cross stiffness plate’, sub-categorised according to the Eurocode into FAT Class 80. Based on the good results of UIT, Stuttgart University suggested a new calculation regulation, as improvement of the notch case after UIT for materials S355 (+2 from 80 to 100) and S690 (+4 from 80 to 125). In most cases, the actual values through UIT for the material S690 reached a value of above 160 (base material).



L = 25mm, R = 0,1

Steel	Eurocode 3, Part 1.9		TIG Dressing		UIT*	
	$\Delta\sigma_C$ [N/mm²]	m [-]	$\Delta\sigma_C$ [N/mm²]	m [-]	$\Delta\sigma_C$ [N/mm²]	m [-]
S355	80	3	100	3	100	5
S460					112	
S690					125	

* max. Compressive Stress: $\sigma_{min} \leq 0,25\ f_y$
max. FAT Classe 125 N/mm²

Table III: The future Eurocode 3, Part 1.9

5.2 Third party approval

Especially in the offshore and petrochemical industries, a third party approval of the design is necessary. Certifying Authorities like Bureau Veritas, Lloyds Register, DNV and ABS have a long-standing history in design reviews and approval. Their experience and know-how is assured through specific codes and standards, which help or lead a designer through the design and engineering processes. These codes and standards were leading for a long time, but the design philosophy has changed to the usage and approval of a safety case: the designer prepares a risk analysis including mitigation of identified risks. The Certifying Authority assesses and approves the safety case.

New technologies like UIT introduce a certain risk. However, the amount of international test results incorporated in many S-N curves can give enough back-up to support the benefits and minimise the risk to a level of acceptance. The remaining risk can be covered by additional testing, if required. On top of that UIT has obtained general approvals to apply UIT as an alternative PWT from most Certifying Authorities and several specific approvals.

6 FATIGUE DESIGN WITH UIT: REDUCTION OF CAPEX AND OPEX

6.1 Crane design: development of 60m and 90m long crane booms of HSS

The first manufacturer who has implemented UIT in its cranes is Rusch Cranes in The Netherlands. For the calculation and design according to the crane norm DIN 15018, cranes are divided into groups of stress levels. These are independent to the implementation of the crane and are determined by the stress range (load number) as well as the stress collective (stress level). The allowed stress is dependent upon the notch cases of the weld detail. Through the post weld treatment by UIT it is possible to improve a bad notch case e.g. K4 to a notch case of K2. It is thereby possible to increase the allowed load of the crane or to reduce its weight. With minimal weights, for example, for those of the crane boom, the load capacity can be raised, with the same stability against collapse. After the latest stand of Codes, the use of high strength steels is in many cases pointless, since with regards to the dynamic load force there are no advantages, where with notched constructions fatigue strength is independent to the tensile stress. In the research project P 620 [4] it was, however, determined that the UIT effect is accordingly greater the higher the yield strength of the base material, as higher compressive residual stresses can be incorporated. For Rusch this has resulted in a 60m long crane boom of S960 and a 90m long crane boom is under development.

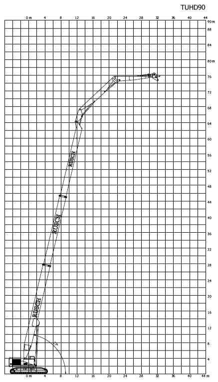


Figure 10**:** Rusch demolition crane boom of S960. The 90m boom under design; the 60m boom in operation.

6.2 Offshore units design: rehabilitation of a semi-submersible

The semi submersible Ton van Langeveld of Noble Drilling was build in 1986 and was in need of an upgrade. The engineering of the upgrade was subcontracted to Gusto MSC, group company of SBM Offshore. Fatigue of offshore units like semi submersible Noble Ton van Langeveld is most times governed by wave induced loads, either directly from the water pressure variations over the shell of the unit and associated loads, or directly by inertia forces as a result of wave induced motions. To be able to perform a fatigue analysis for an offshore unit, therefore first the operational wave climate must be defined. Using the wave pressures and motions, the actual occurring stresses are than calculated by means of a Finite Element Model.

Applying the relation between wave cycle and stress cycle to the wave height distribution contained in the wave scatter diagram, it is possible to establish for each structural detail of the semi sub a long term distribution of stress cycles: for various stress levels the number of cycles is indicated that the particular stress level is exceeded. With this long term distribution of stress cycles and an applicable S-N curve the occurrence of fatigue damage can be determined. With the help from applicable S-N curves with UIT, one can determine the possible fatigue enhancement.

The structural details with fatigue damage were the middle columns, K-Joints, trumpets, outer columns and chain lockers, made of steel EH36. This exercise resulted in a log book with critical welds and weld length to be treated with UIT, see figure 12. The upgrade of the semi submersible was executed under ABS classification.

6.3 Bridge design: 105 m. Road Bridge at Suhl-Lichtenfels

For the building of the new A73 highway from Suhl to Lichtenfels, North Bavaria, a modern slim bridge was planned and designed. A concrete deck is supported by a steel structure. The slim steel pipe construction of S355, consists of 2 top chords and 2 under chords, connected through welding to the diagonal pipes. The pipe diameter of the lower chord comprises 850 mm. and the wall thickness a maximum of 50 mm. As this bridge did not met the applicable Standard, peer approval had to be sought. During the examination of the static calculation by Prof. Dr. Mangerig of the Munich Defence University,, it was determined that the permitted stresses at certain joint points exceeded valid regulations. A further expert, Prof. Dr. Bucak proposed, on the basis of previous positive experiences, UIT as a possible solution. Pre-tests on pipe joints showed an Improvement Factor of 5. On the basis of this positive result, the High Way Board North Bavaria has awarded a contract for UIT of in higher stressed pipe-joints.

Figure 12: Semi submersible Noble

Figure 13**: J**oint of the A73 roadway bridge

7 SUMMARY

Esonix® UIT has entered a stage of general acceptance in the industry of maintenance and renewal. With UIT industry has been provided a technology to improve fatigue life [n] with a factor ≤ 8 or to increase the fatigue stress [MPa] with a factor ≤ 2. The next step is the acknowledgement of UIT in the design and manufacturing of new structures. Since 1998, UIT has been tested at many international R&D programmes at universities such as Lehigh, Stuttgart, Hannover and Braunschweig. The results are incorporated in S-N curves with various types of steel (S355, S460, S690), weld details and stress ratios (R). Certifying Authorities have given several Approvals. The available S-N curves offer a designer or engineer the position to choose between designing a weld detail using FAT Class 80 or to design a similar weld detail via UIT and obtaining FAT Class 125. The choice for UIT will offer benefits to the industry by a reduced capital and operational expenditure, due to a reduction in down-time, material savings and enhancement of fatigue life.

8 ABOUT THE AUTHORS

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