EUROSTEEL 2014, September 10-12, 2014, Naples, Italy

FATIGUE ASSESSMENT OF NON-LOAD CARRYING FILLET WELDS

After seams' repair and treatment procedures

Hartmut Pasternak, Agnieszka Chwastek

Brandenburg University of Technology, Dept. Steel and Timber Structures, Cottbus, Germany
hartmut.pasternak@tu-cottbus.de, agnieszka.chwastek@tu-cottbus.de

INTRODUCTION

In the building sector there is a strong shift in investment allocation from newer structures towards restoration and maintenance. Additionally unforeseeable variations in the operating conditions which could not be taken into consideration during the design phase, e.g. longer operating times, higher loads, and the wish for longer use further limits the service life [9]. Often cyclic loads are applied to welded steel structures. The fatigue strength of whole structure decisively depends on details, which are mostly from the welded joints. Weld toes and ends are the most critical locations that fatigue cracks are more likely to occur and later grow. Therefore the weld seams currently must frequently undergo preventative renovations. In fact there is no a proper uniform assessment concepts for the load carrying ability of cyclically loaded weld seams subsequent to repair. The main aim of this research is to determine influence of seams' repair and treatment procedures and then appraise the assessment concepts based on the most prevailing concepts, included in EN 1993-1-9 or EN 13001-3-1 i.e. nominal and structural (hot-spot) stress approach. Particular attention is paid to hot-spot stress approach because this method is more detailed and efficient by welded joints. Like a specimen to be investigated is used a transverse non-load carrying attachment with fillet welds.

1 ASSESSMENT CONCEPTS

1.1 Basic

There a few basic approaches to fatigue life prediction of welded components, which differ in the level of stress-raisers taken into account by the analysis. The level of stress analysis in the design phase must match that used in the determination of fatigue strength data. Factors that are ignored in the analysis, are left to the fatigue strength criteria determined empirically, e.g. S-N curve [5]. In this paper particular attention is paid to the two first approaches, included in [1] or [2] i.e. nominal and structural (hot-spot) stress approach (explained beneath). They are still nowadays the most prevailing but there are not included any corrections due to repair or treatment procedure.

1.2 The nominal stress approach

In general the nominal stress is the stress calculated in the sectional area of potential region of crack initiation under consideration (parent material or weld seam) using simple beam theory, disregarding the local stress concentration of the welded joint. However, in practice there exist also any certain macro-geometrical features, as well as stress fields in the vicinity of concentrated loads and reaction forces. The test pieces, from them the catalogues of classified detail (fatigue strength) were established, contain various attachments giving rise to structural discontinuity effects, and various welds, but usually no aforementioned macro-geometric effects. For that reason they should be additionally taken into account by determination of the nominal stresses by using the appropriate stress raisers, see *1.4.1*.

Although there is no doubt that the specimens tested to generate the S-N data, contained some misalignment, like e.g. fabrication inaccuracy and welding distortion that in general has not been quantified. Therefore, it is normally assumed that design data are only applicable to aligned joints, or perhaps to joints containing very small amounts of misalignments [5]. Consequently, all type and extent of expected or detected misalignment should be assessed in the stress calculations, see *1.4.2*.

The nominal stress included the stress raisers factor is called like modified nominal one.

An advantage of application of the nominal stress approach is a relatively little workload needed, although it is rather preferable for easy geometries. By welded connections particular attention is paid to hot-spot structural stress approach because this method is more detailed and efficient in such cases. The design value of nominal stress ranges should be determined, as follows *Eq. (1)*.

$$\gamma_{Ff}\Delta\sigma_{E,2} = \lambda_1 \times \lambda_2 \times \lambda_i \times \ldots \times \lambda_n \times \Delta\sigma(\gamma_{Ff} Q_k) \tag{1}$$

where $\Delta\sigma(\gamma_{Ff} Q_k)$ is the stress range caused by fatigue loads specified in EN 1991,

λ_i are damage equivalent factors depending on the spectra as specified in the relevant parts of EN 1993.

The design value of modified nominal stress ranges should be determined, as follows *Eq. (2)*.

$$\gamma_{Ff}\Delta\sigma_{E,2} = k_f \lambda_1 \times \lambda_2 \times \lambda_i \times \ldots \times \lambda_n \times \Delta\sigma(\gamma_{Ff} Q_k) \tag{2}$$

where k_f is the stress concentration factor to take account of the local stress magnification in relation to detail geometry not included in the reference $\Delta\sigma_R$-N-curve [1].

According to [1] the fatigue verification for each of stress categories is the same. The stress ranges due to frequent loads shall be verified under *Eq. (3)*.

$$\frac{\gamma_{Ff}\Delta\sigma_{E,2}}{\Delta\sigma_C / \gamma_{Mf}} \leq 1,0 \tag{3}$$

where $\Delta\sigma_C$ is the reference value of the fatigue strength at N_C=2 million cycles,

γ_{Mf} is a partial factor for fatigue strength $\Delta\sigma_C$.

1.3 The structural stress approach

The structural (or geometrical) stresses include both nominal stresses and the effects of structural discontinuities due to structural detail of the welded joint, but excluding the notch effect of the weld profile itself, like toe transition. The hot spot is the critical point (usually weld toe) in a structure, where fatigue cracking can be expected to occur due to a discontinuity and/or a notch. It is generally not feasible to determine the structural hot spot stresses using analytical methods. It is possible just through extrapolation to hot spot the results taken from FEA or strain gauges measurements. The extrapolation to the weld toe is carried out under consideration of stresses from two or three reference points at certain distances from the weld toe. Thus, the structural hot spot stresses used in this approach do not include any nonlinear stress peak caused by weld, *Fig. 1a*. They are linearly distributed across the plane thickness and consist membrane and shell bending stress components, *Fig. 1b*. The fatigue strength data based on the hot spot approach are determined also from strain measurements of specimens near the point of crack initiation taken perpendicular to and from several sections along the weld toe. Then comparable to previous the results are extrapolated to the weld toe.

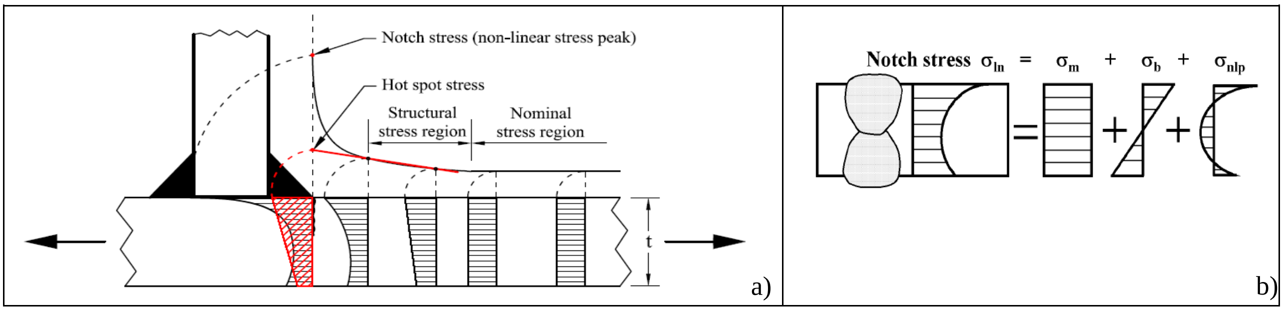

Fig. 1. a) Definition of structural hot-spot stress [12]; b) Local notch stress at a weld toe, comprising membrane and shell bending stresses (structural) and a nonlinear stress peak [7]

Obviously in this case also any possible misalignment has to be taken explicitly into consideration in the FEA model or by applying an appropriate stress magnification factor, see *1.4.2*. The design value of geometrical (hot spot) stress ranges should be determined, as follows *Eq. (4)*.

$$\gamma_{Ff}\Delta\sigma_{E,2} = k_f\,(\gamma_{Ff}\Delta\sigma^{*}_{E,2}) \qquad (4)$$

where k_f is the stress magnification factor.

1.4 Stress raisers

The effect of local increases in stress due to geometric features such as structural discontinuities or misalignment can be taken into account by the use of appropriate stress concentration factors, in general marked k_f [6].

1.4.1 Stress concentration factor

The effects of macro-geometric features as well as stress fields in the vicinity of concentrated loads and reaction forces are used in conjunction with the nominal stress through use of stress concentration factor, k_t. These effects usually cause a significant redistribution of the membrane stress field across the whole section *Eq. (5)*. Whereas the structural discontinuities may also cause a local concentration in the membrane stress field as well as local shell bending stresses. They belong normally to calculation of structural stress if are not included in detail geometry of hot spot S-N data. In spite of time and cost required, FEA is mostly applied for establishing the stress concentration factor.

$$\sigma_{nom.\mathrm{mod}.t} = k_t\sigma_{nom} + ...Q \qquad (5)$$

1.4.2 Stress magnification factor

Some allowance for misalignment is already covered by the fatigue resistance S-N curve (nominal and also structural). If the misalignment exceeds this amount then the stress concentration factor is required to be calculated according to, $k_{m,eff}$, *Eq. (6)*. There are to distinguish axial and angular misalignment separately, *Eq. (7)*.

$$k_{m,eff} = \frac{k_{m,calculated}}{k_{m,already\,\mathrm{cov}ered}} \qquad k_m = 1 + (k_m - 1)_{axial} + (k_m - 1)_{angular} \qquad (6), (7)$$

Either the applied stress is multiplied by $k_{m,eff}$ or the allowable stress range obtained from the relevant resistance S-N curve is divided by it [7]. The secondary bending stress is obtained, as follows *Eq. (8)*.

$$\sigma_{II.b} = k_m\sigma_{nom.m} - \sigma_{nom.m} = (k_m - 1)\sigma_{nom.m} \qquad (8)$$

2 SEAMS’REPAIR AND TREATMENT PROCEDURES

2.1 Recognition of welds cracks at weld toe

Non-destructive testing methods (NDT) like i.e. ultrasonic or eddy current measurements are capable of detecting in practice the length or depth of surface-breaking flaws. When the flaws length is not yet considerable it is rather recommended to carry out the repair procedures by removing area of crack and make re-welding. Before repair welding, the crack at weld toe shall be completely removed by grinding. The final weld surface and the transition to the base material shall be smooth. Removal of defects is verified by local visual inspection, aided by applicable NDT methods [4].

2.2 The post weld treatment

The post-weld treatment is generally used for stress relief, *Fig. 2*. The purpose of stress relieving is to remove any internal or residual stresses that may be present from the welding operation. Stress relief after welding may be necessary in order to reduce the risk of brittle fracture, to avoid subsequent distortion on machining, or to eradicate the risk of stress corrosion. For this project the post-weld treatments with application of high-frequency peening process is planned since it is the most frequently used procedure for renovating weld seams. The specimens with fillet welds are suitable for the application of the post-weld treatment, since it improves the weld toe zone where the cracks are expected to occur.

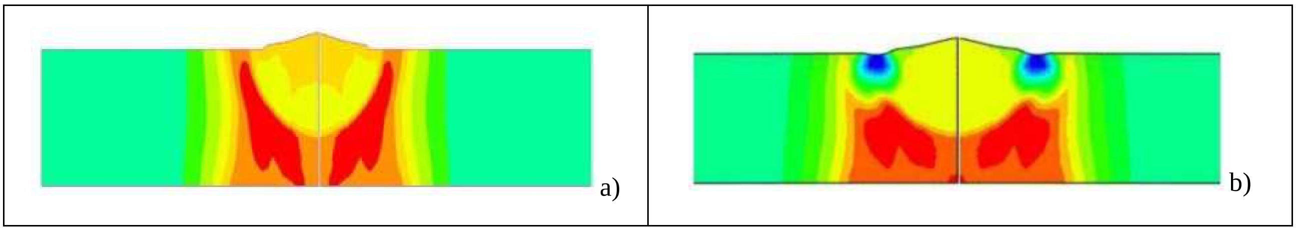

Fig. 2. Weld connection with residual stresses a) after welding; b) after post-weld treatment [13]

3 EXPERIMENTAL INVESTIGATION

3.1 Fatigue tests

The fatigue strength test analyses (*Fig.3*) are divided into three groups. Group I – defect-free weld seams, group II – flawed weld seams renovated by grinding the existed crack and re-welding, group III – analogous to group 2 but supplemented by post-weld treatment methods. The specimens are transverse non-load carrying attachment with fillet welds. The steel grade is 355J2N.

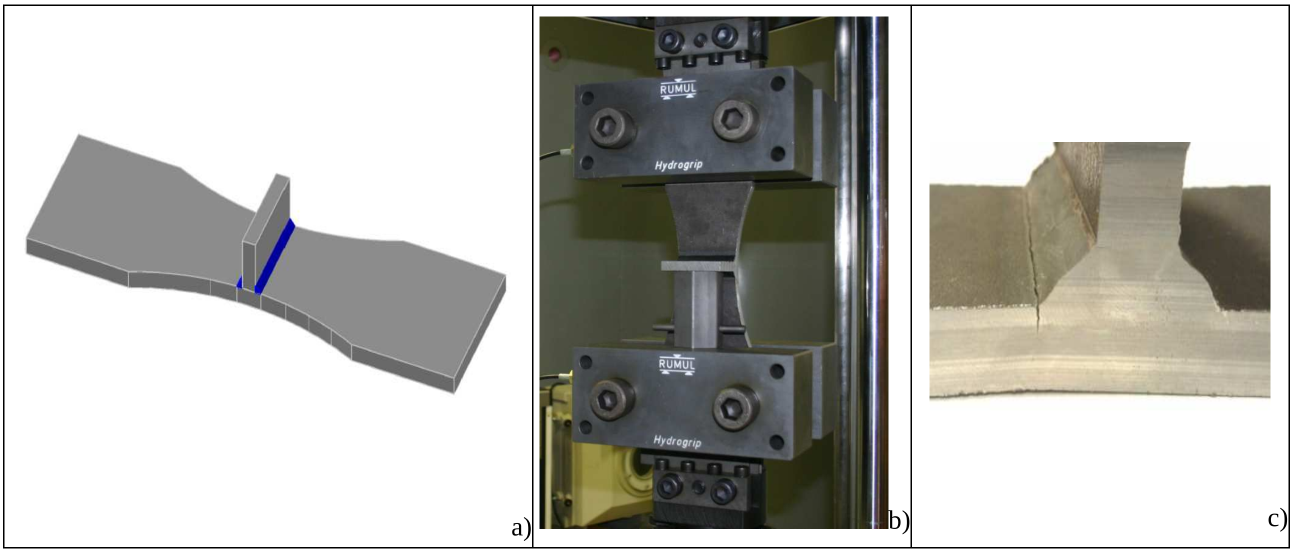

Fig. 3. a) Geometry of specimens; b) Hydraulic fatigue test machine; c) Crack at weld toe of one of specimen

Firstly each of specimen for group I was separately cut from sheets of steel, prepared in advance. Metal active gas welding (MAG) has been used. Then the fatigue tests were carried out. The fatigue strength can be compared with case details from [1] for the most similar geometry ($\Delta\sigma_C$=80N/mm^2). In group II the potentially existing cracks were removed by grinding of weld toe area. It was made using a milling machine. The excavated groove is assumed to be 3mm deep (30% of sheet thickness). Re-welding was carried out using arc welding with electrode. At the end each of specimen is subjected to dynamic tests. The high-frequency peening process which changes harmonic vibration to mechanic impulses is carried out for group III. Since of beneficial compressive residual stresses the enhancement of fatigue life is expected.

3.2 Analyses of fatigue strength

The fatigue strength component tests are performed with the aid of the classical S-N (*Wöhler*) test. The procedure for the fatigue analysis for welded structures is based on the assumption that it is only necessary to consider ranges of cyclic stress in determining the fatigue life. As a project results for the fatigue strength, a correlation of identical geometric construction details to different classes of notch types is expected as a function of the conditions prevailing during the weld seams' repair and treatment procedures. *Fig. 4a* shows results of fatigue tests from group I and II determined according to the nominal stresses. *Fig. 4a* indicated the difference of fatigue strength, just for group I, between the nominal and modified nominal stresses, which already included influence of macro-geometric and misalignment effects. The analysis of group III is right now planned to examine. Each *Wöhler*-curve was determined from 15 test results for five different levels of load, in range between $\Delta\sigma_i$=207 ÷72N/mm^2 calculated in narrow cross section of sheet plate. The kind of load is alternating axial tensile with stress radio, R=0,1 with frequency of loading 30Hz.

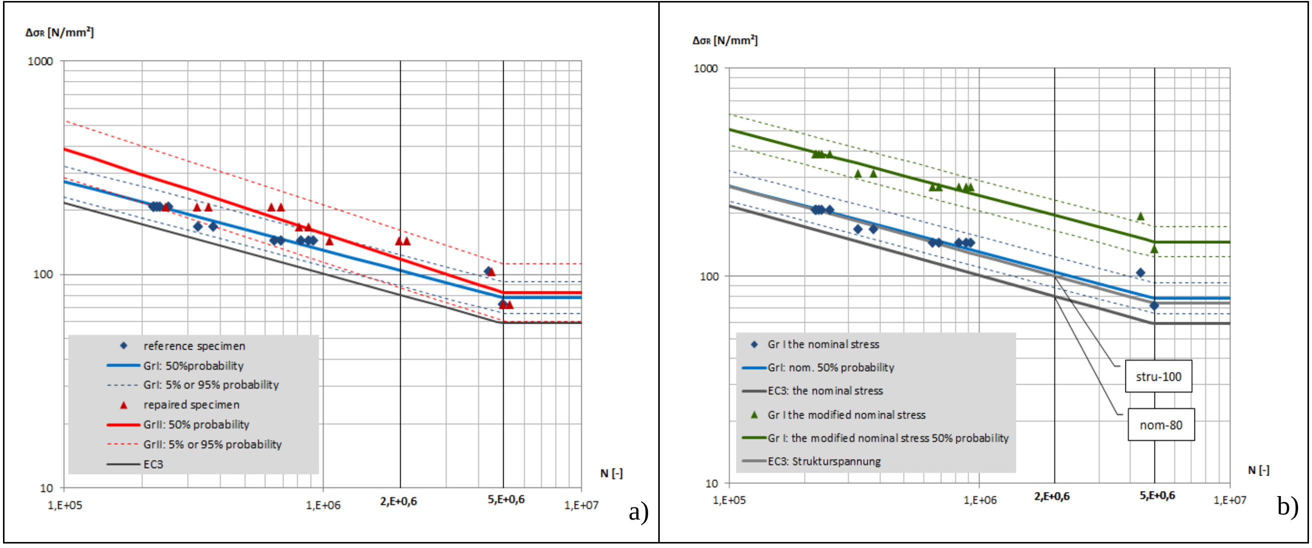

Fig. 4. a) Fatigue test results for group I and II; b) The nominal and modified nominal stresses for group I

The planned numerical investigations serve to reduce the number of the required experimental tests and give essential data for the calculation of stress approaches. An informative picture regarding to material and stress states is generated for both the weld seams' original state (*Fig. 5*) as well as the repaired and renovated states.

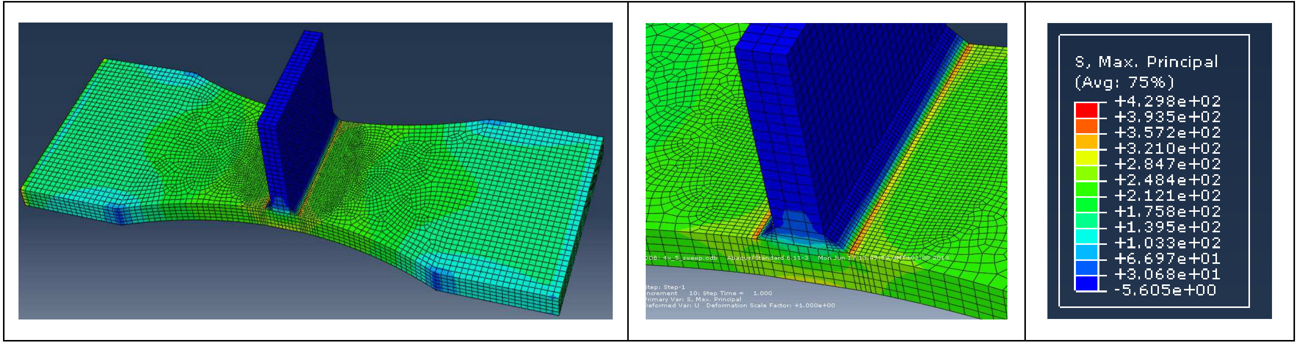

Fig. 5. FE analysis of structural hot-spot stress of group I

3.3 Accompanying test

The manufactured welded specimens are metallographically examined in order to ensure comparability of the weld seam, *Fig. 6*. The macroscopic specimens of the welded seams allow determining the weld-pool geometry, the seam profile and hardness. Additionally, the residual stresses are measured transverse to the weld seam using x-ray analyses, particularly in cases of weld repairs. Besides fatigue tests the tensile tests of specimens are also carried out to compare material static behaviour.

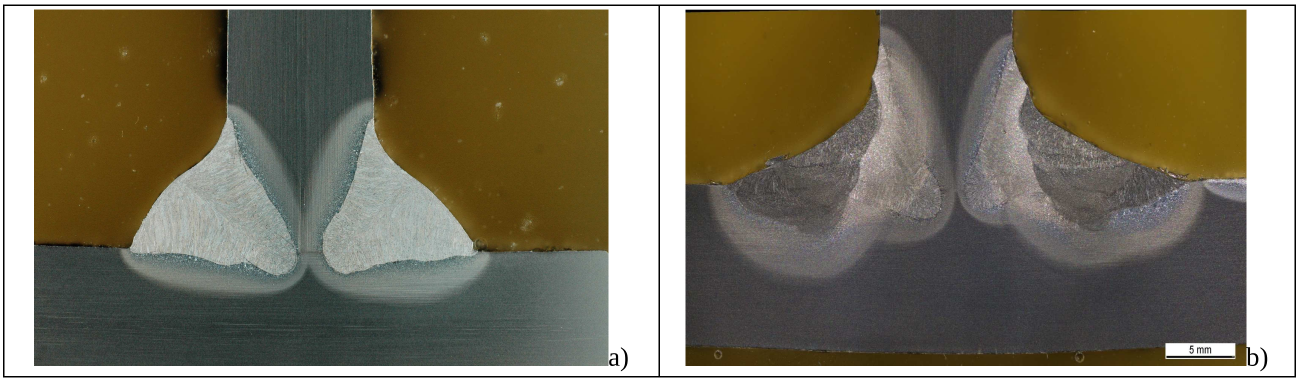

Fig. 6. The heat affected zone a) by original weld seam; b) after seam' repair

4 CONCLUSIONS

A scatter of results from group II (flawed weld seams renovated by grinding the existed crack and re-welding) is considerably larger than group I (defect-free weld seams). Taking into consideration the survival probability calculations, the fatigue strength is not extremely improved compared to original ones, but it is hold at comparable equal level. It has been observed that by removing the cracks at weld toes and re-welding, again the resistance of the original specimen can be achieved. The considerable enhancement of fatigue life is more likely to be achieved after additional use of post-weld treatment.

REFERENCES

[1] EN 1993-1-9, Design of steel structures. Fatigue, 2003.

[2] EN 13001-3-1, Cranes. General design-Limit States and proof of competence, pp.36-47, 57-81, 2008.

[3] DIN Fachbericht 103:Stahlbrücken. *Steel bridges*, pp.121-146, 169-186, Beuth Verlag, 2003.

[4] NORSOK; Structural Steel Fabrication, pp.24-25, October 2011.

[5] Niemi, E, "Stress Determination for Fatigue Analysis of Welded Components", Doc. IIW 1221-93, pp. 3-5, 12-16, 19-32, Lappeenranta University of Technology, Lappeenranta 1995.

[6] Niemi, E, Fricke, W, Maddox, S, J, "Fatigue Analysis of Welded Components. Designer's guide to the structural hot-spot stress approach", Doc. IIW 1430-00, pp. 3-29, 2006.

[7] Hobbacher, A, "Recommendations for fatigue design of welded joints and components.", Doc. IIW XIII-1539-96/XV-845-96, pp. 13-80, 99, 135-138, Paris, October 2008.

[8] Dürr, A, "Zur Ermüdungsfestigkeit von Schweißkonstruktionen aus höherfesten Baustählen bei Anwendung von UIT-Nachbehandlung",pp. 25-34, 44-45, Institut für Konstruktion und Entwurf der Universität, Stuttgart, 2007.

[9] Radaj, D, Sonsino, C, M, "Ermüdungsfestigkeit von Schweißverbindungen nach lokalen Konzepten", Verl. für Schweißen und Verwandte Verfahren, DVS-Verl., Düsseldorf, 2000.

[10] http://www.pfeifer.de/de/hifit/

[11] Doerk, O, Fricke, W, Weissenborn, C, "Comparison of different calculation methods for structural stress at welded joints", International Journal of Fatigue 25, pp. 359-369, Hamburg 2003.

[12] Aygül,M, "Fatigue Analysis of Welded Structures Using the Finite Element Method", pp.5-19, Department of Civil Enigineering, Steel and Timber Structures, Chalmers University of Technology, Gothenburg, 2012.

[13] Schröder, H, Ch, Gerster, P, Schäfers, F, "Neue Prüfkonzepte und Verfahren zur Schweißnaht-Nachbehandlung", VGB Power Tech 8, Mannheim, Ehingen, Kerpen, Germany, 2010.