MARITIME

RECENT FATIGUE AND FRACTURE RESEARCH ACTIVITIES

SAFER, SMARTER, GREENER

CONTENTS

1

INTRODUCTION

In conventional strength assessments, the safety of structures are considered under static maximum loads, i.e. the design loads.

However, ship structures are to a large extent affected by stresses varying over time. These stresses are mainly caused by the seaway, by propulsion plant excitation forces as well as by changes in loading conditions (Figure 1).

During past years, evaluation of fatigue life of ship structures has gained significance because of the continuous trend towards highly optimised structures and the intensified use of higher tensile steel. Special topics are lightweight structures with thin plates down to 3 mm used for yachts and passenger vessels on the one hand, and on the other hand the use of thick steel plate up to 100 mm which are commonly used in the upper flange of large container vessels.

It has to be emphasized that not only the design of main structural components are of importance for a good fatigue performance, but also the application of outfitting details are very often reasons for fatigue cracks. Fatigue cracks start typically either from weld seams or from free plate edges. Two examples for insufficient fatigue resistance are given in Figure 2 (Crack initiation at a plate edge) and Figure 3 (Crack initiation at a weld seam).

Advanced fatigue experience is needed with respect to

- Avoidance of cracks in cyclic loaded structural components
- Prediction of fatigue lifetime of ship structures
- Verification of damages in view of appropriate repair measures

Figure 1 – Fatigue loading

Benefits for the clients are

- Utilisation of structural components at a balanced level
- Reliable ships
- Reduced repair costs within service time

Before the merger of both societies, former DNV as well as former GL were very active in the field of fatigue:

- Long-term experience in fatigue assessment of structural components
- Participation in national, European and international research projects and committees
- Know-how in development and application of nominal and local stress concepts
- Know-how in development and application of spectral analyses
- As the first classification society, GL introduced fatigue requirements into the rules

After the merger, DNV GL continues research and development activities. Recently performed as well as ongoing activities will be described hereafter.

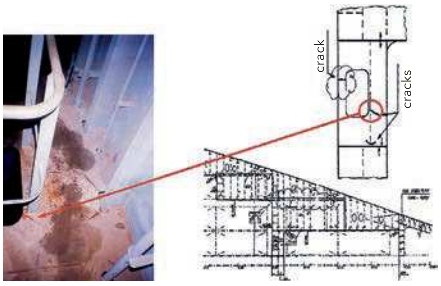


Figure 2
Crack initiation at a plate edge

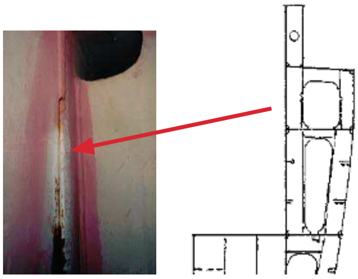


Figure 3
Crack initiation at a weld seam

2

OVERVIEW OF FATIGUE- AND FRACTURE MECHANICS-RELATED ACTIVITIES

A big variety of topics are covered by DNV GL fatigue activities such as:
- Experimental fatigue testing of welded joints as well as plate edges
- Development and application of calculation techniques as nominal stress, hot-spot stress and notch stress approach
- Development and application of spectral fatigue analysis

For welded joints, special attention was on:
- High cycle and low cycle fatigue
- Thin and thick plates
- FCAW, EGW and laser welding
- As welded condition and post-weld treatment

And for plate edges:
- High cycle and low cycle fatigue
- Thin and thick plates
- As cut condition and post-cutting treatment

In addition, several investigations were done using fracture mechanics technique, also by experimental as well as by theoretical work. Here the focus was laid on safety aspects of butt weld joints at thick plates made of high-tensile steel HT47. The following aspects were investigated in detail:
- Cyclic crack growth parameters
- Fracture toughness
- Double master curve concept
- Influence of welding residual stresses
- NDT possibilities and sensitivity

For European funded projects, partners were:
- Shipyards
- Research institutes
- Technical universities

JDPs were done in cooperation with partners such as:
- Korean shipyards
- Korean steel mill
- Other CSs

Besides this, DNV GL is participating in national as well as international committees such as the German welding society DVS and the International Institute of Welding IIW.

Due to the high utilisation of large containerships, special attention on the design of the upper flange of the ship hull is needed. This part of the ship is characterised by the use of thick plates made of high-strength steel. Both thick plates as well as high-strength material are not beneficial from a fatigue point of view. So fatigue becomes a limiting factor for design.

This is and was the reason for DNV GL to initiate and to participate in many research activities on fatigue and fracture mechanics of thick plates and high-strength material.

3

SELECTED PROJECTS

In the following, brief descriptions of selected projects are given. The projects were carried out by DNV GL Maritime Technology as well as by Maritime Advisory. Most project results are published by conference papers as summarised in the end.

3.1

Fatigue strength of YP47 welds [1], [2]

3.1.1 Abstract

In order to investigate the fatigue strength behaviour of YP47 welds, a Joint Development Project (JDP) between the Korean Committee of Shipbuilding Steel Development and Germanischer Lloyd (GL) was established. Main objectives of the JDP were the investigation of the thickness influence at modern high-quality YP47 welds and investigation of a potential influence of the yield strength on the fatigue strength. To reach the goal, an extensive fatigue test programme accompanied by calculations was carried out. The test programme consisted of butt weld and longitudinal stiffener specimens in a thickness range between 25 mm and 75 mm. In general, a good fatigue performance of the specimens was observed in the tests. The results regarding the thickness influence were different compared to the thickness influence given by the rules and recommendations. This is especially valid for the longitudinal stiffener specimens where no clear thickness influence could be detected. Furthermore, the tests showed a yield strength influence on the fatigue strength of welded joints, but with respect to the small data basis a generalisation of these results is actually not possible. As a co-product of the JDP, limitations of the current structural and notch stress approaches for fatigue assessment were detected.

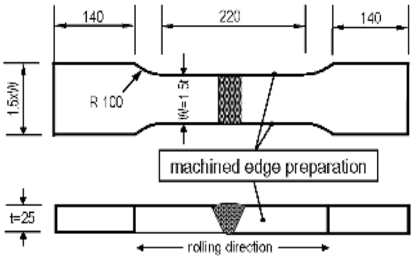


Figure 4 – Butt weld specimens (thickness 25 mm)

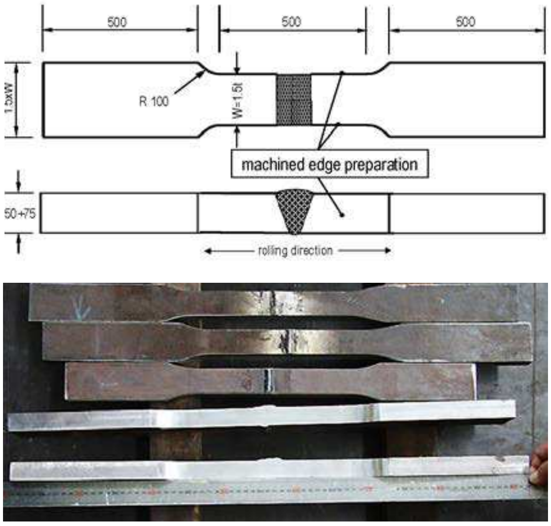


Figure 5 – Butt weld specimens (thickness range between 50 and 75 mm)

TABLE 1: TRANSVERSE BUTT WELD SPECIMENS – TEST MATRIX

Series	t [mm]	Material	Welding process	Condition	No. of Specimen
A1.1: 25_A, 25_B, 25_C	25	YP47	FCAW	as welded	21 (7, 7, 7)
A1.2: 50_A, 50_B, 50_C	50	YP47	FCAW	as welded	21 (7, 7, 7)
A1.3: 75_A, 75_B, 75_C	75	YP47	FCAW	as welded	21 (7, 7, 7)
A1.5 *: 75_A2	75	YP47	FCAW/EGW	as welded	15

* To cover potential effects of the welding procedure.

3.1.2 Test programme and main results

In order to investigate the thickness influence, a complex test matrix for butt welds containing three different plate thicknesses and two different welding procedures (multi-pass FCAW as a standard and a combined EGW/FCAW process as a special) was set up according to Table 1.

The fatigue tests were carried out on resonance testing machines at RWTH Aachen as well as at TUHH Hamburg. The test frequency was approximately 30 Hz for both testing machines. All tests were carried out under axial load with a stress ratio of $R \approx 0.1$ simulating realistic loading conditions for the coaming and coaming top area of large container vessels. For specimen scantlings, see Figures 4 and 5.

The tests were performed at several stress range levels to get information about the FAT class as well as the slope of the S-N curve ("rope of pearls"). See Figure 6.

The figure shows that all specimens have good fatigue behaviour; all values are above the design S-N curve (FAT 80). The thickness effect is as expected, the thick plate specimen results are close to the FAT 80 line while the thin plate results are apart from that. The intermediate thick plates are in between.

The fatigue tests of the longitudinal stiffener specimens were carried out in a similar way as the fatigue tests of the butt weld joints. A symmetric double stiffener design was chosen for the specimens in order to avoid transverse vibration effects while testing in the resonance testing machines.

While the tests of the 25 mm thick specimens were carried out at the TUHH, the tests of the 75 mm thick specimens were carried out at RWTH. The test matrix of the longitudinal stiffener fatigue tests is presented in Table 2. Sketches of the specimens can be found in Figures 7 and 8. The cover page figure shows an 80 mm thick specimen after successful testing.

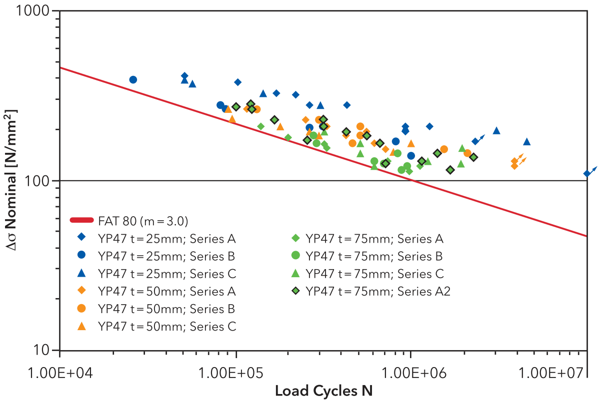


Figure 6 – S-N diagram for butt welds (nominal stress concept)

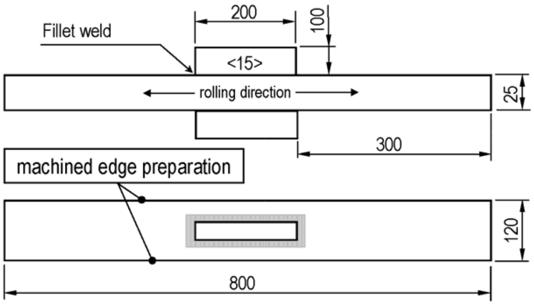


Figure 7 – Longitudinal stiffener specimen, t = 25 mm

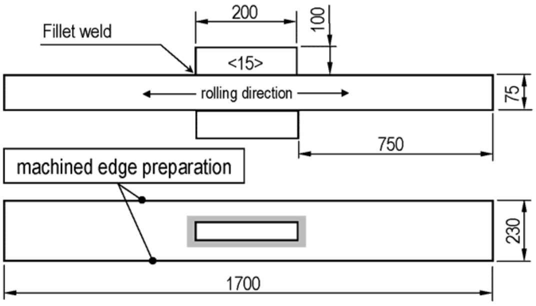


Figure 8 – Longitudinal stiffener specimen, t = 75 mm

TABLE 2: LONGITUDINAL STIFFENER SPECIMENS

Series	t [mm] plate / stiffener	Material	Welding process	Condition	No. of Specimen
25_YP24	25 / 15	YP 24	FCAW	as welded	15
25_YP36	25 / 15	YP 36	FCAW	as welded	15
25_YP47	25 / 15	YP 47	FCAW	as welded	15
75_YP36	75 / 15	YP 36	FCAW	as welded	15
75_YP47	75 / 15	YP 47	FCAW	as welded	15

The test results are presented in the S-N curve in Figure 9. Again it can be seen that the test specimens fit well to the design values given in the rules. From the diagram it can be seen that no pronounced thickness effect as well no pronounced material effect has been found.

In rules and guidelines, the thickness influence is usually considered by means of a correction factor f_t according to the equation:

$$f_t = \left(\frac{t_{ref}}{t_{eff}}\right)^n \qquad \Delta\sigma_{perm}(t) = f(t)\cdot\Delta\sigma_{perm}(t_{ref})$$

with:

t_{ref}	reference plate thickness (often taken as 25 mm)
t_{eff}	effective plate thickness
n	exponent of the thickness influence law

The exponents n are given in Table 3. The butt weld test are very well in accordance with recommendations given by International Institute of Welding IIW. GL values are slightly lower, as smaller misalignments for thick plates were already considered. For the longitudinals, no thickness influence has been found which is in contrast to IIW recommendations. But it has to be emphasized that for all base plate thicknesses, thin attachments with t = 15 mm have been investigated. From other tests it is known that in case of thick attachments on thick base plates, a thickness effect is present.

Finally, the thickness effect for butt welds has been investigated by notch stress calculations (Figure 10). The result is a thickness exponent of n = 0.15. This is smaller than the experimental result, but the calculation can reflect the crack initiation only and not the crack propagation.

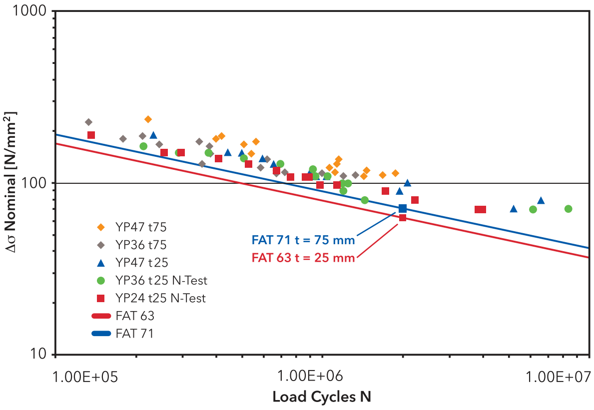
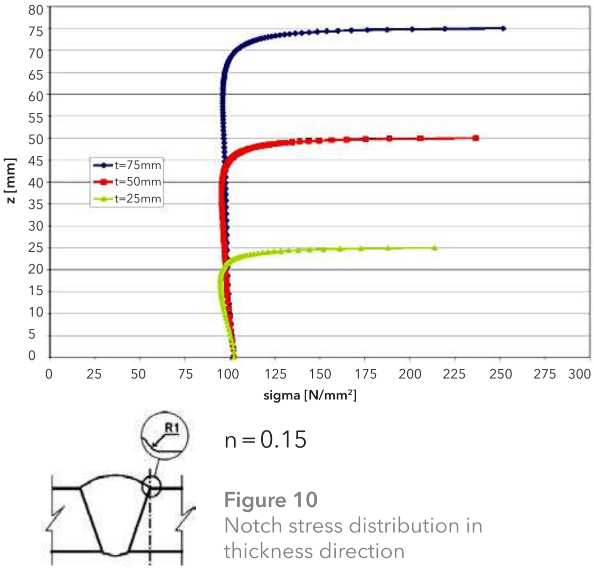


Figure 9 – S-N diagram for longitudinal stiffeners (nominal stress concept)



n = 0.15

Figure 10
Notch stress distribution in thickness direction

TABLE 3: EXPONENT N FOR THICKNESS CORRECTION

Exponent n	IIW	GL	Test
Butt welds	0.20	0.17	0.21
Butt welds ground flush	0.10	–	
Longitudinal stiffeners	0.30	0.00	0.00

3.1.3 Summary

Overall results of this JDP can be summarised as follows:

- YP47 welds show good fatigue performance
- 10% increase for longitudinal stiffeners
- Thickness effect for butt welds confirmed
- No pronounced thickness effect for longitudinal stiffener
- Further investigations recommended

Longitudinal stiffener:

- Nominal stress approach fits well
- Hot-spot stress approach is slightly unconservative (calculation)
- Notch stress approach is very conservative
- S-N curve knuckle might be shifted left

- No need to adjust GL rules

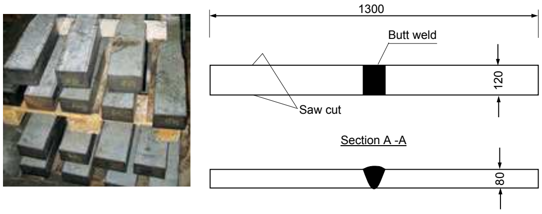


Figure 11 – Butt weld specimens

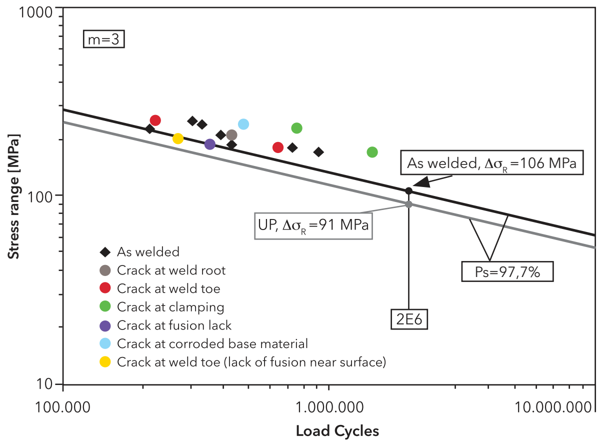


Figure 12 – S-N diagram with butt weld results

3.2
Fatigue tests of post-treated butt welds and plate edges of 80 mm plates [3]

3.2.1 Abstract

Within this JDP, fatigue tests of 80 mm thick plates have been performed. The objective of the fatigue tests was to investigate the effect of different post-treatment methods on the fatigue performance. Test specimens were butt welds as well as plate edges in untreated and post-treated conditions respectively. While for the butt weld specimens, ultrasonic impact treatment (UP) was applied as a post-treatment method, the plate edge specimens were treated by chamfering and different combinations of edge grinding, surface grinding and UP surface treatment. Material was higher tensile steel HT40 for all specimens.

3.2.2 Introduction

It is well known that post treatment of welds and edges can improve the fatigue resistance significantly. For many decades, grinding of welds and plate edges were widely spread. It results in smoothening existing grooves. Also hammer peening is an appropriate technique. In addition to the smoothening effect, it introduces compressive residual stresses which are beneficial too. These two techniques were applied today and rules and guidelines exist. A relatively new technique is high-frequency treatment. The effect on fatigue of butt welds has been investigated over the last years, but the effect on fatigue of thermal cut edges is unknown.

3.2.3 Test programme and main results

3.2.3.1 Butt welds

The 80 mm butt welds were tested at RWTH University in Aachen, Germany. The specimens had a prismatic shape, and before testing they were milled to a “dog-bone” shape to enforce the crack initiation to the weld (Figure 11).

In total, 16 specimens were tested, eight in as-welded condition and eight in UP-treated condition. Material was higher tensile steel E40. Testing condition was axial loading using a resonance testing machine at a testing frequency of about 30 Hz. The butt weld fatigue test results are presented in the S-N curve in Figure 12.

It has been found that the differences in fatigue life of the as-welded and the UP-treated specimens are not significant. A surprising result is that the fatigue resistance for the UP-treated specimens at 50% survival probability is slightly higher than for the as-welded ones, but the design values at 97.7% probability are vice versa. The design value for as-welded condition is FAT 106 and for the UP-treated condition it is FAT 91. The reason for this is that the UP process was not stable in all cases and therefore the UP results have a larger scatter band.

3.2.3.2 Thermal cut edges

The 80 mm thermal cut edge specimens were tested at Technical University Hamburg TUHH, Germany. For specimen scantlings and for four point bending testing arrangement, see Figure 14.

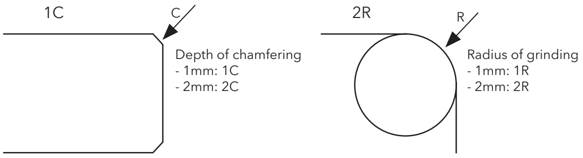
Within this JDP, 32 cut edge specimens were tested in total. The tests were performed for four series with eight specimens each as follows (see also Figure 13):

- 1C, edge chamfering specimens
- 2R, edge rounded specimens
- 2R + G, edge rounded + surface grinded specimens
- 2R + UP, edge rounded + surface treated by ultrasonic peening

The tests were carried out under constant amplitude bending load on a 690 kN resonance testing machine at Hamburg University of Technology (TUHH), Germany. The testing frequency was again about 30 Hz. Material was higher tensile steel E40.

The test results are presented in the S-N diagram in Figure 15.

As a summarisation of the cut edge fatigue test results, the influence of the different post-treatment procedures as well as the effect of different slopes assumed for the fatigue strength assessment are shown in Figure 16, allegorised by the appertaining FAT classes. For this presentation, standard slope 3.5 and 4 as well as the slope derived from the tests were chosen. The relatively low fatigue class for 2R specimens is a little bit doubtful, as this treatment is well proven. Nevertheless, the overall picture is that basic FAT class 140 for treated plate edges is conservative. Following this, a new FAT class 150 was introduced into GL rules. This FAT class can be applied for edge treated plates in combination with refined notch stress calculation.



Reference condition is 1C.

2R will be chosen as grinding condition of hatch corner.

Figure 13 – Thermal cut specimens with edge and surface treatment

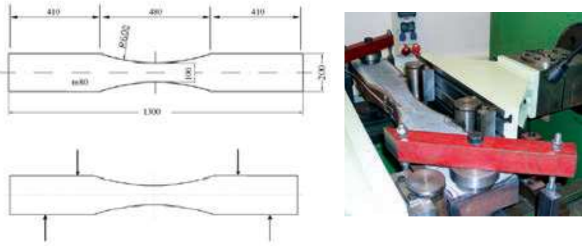


Figure 14 – Thermal cut specimens with testing arrangement

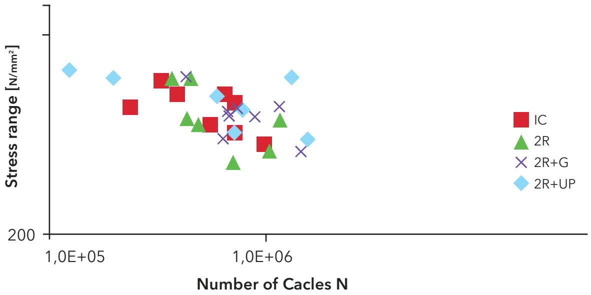


Figure 15 – S-N diagram with thermal cut edge results

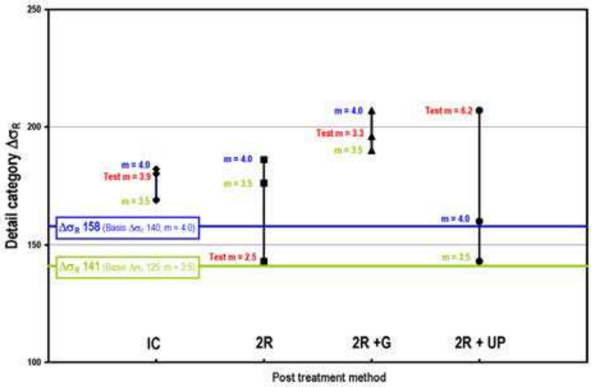
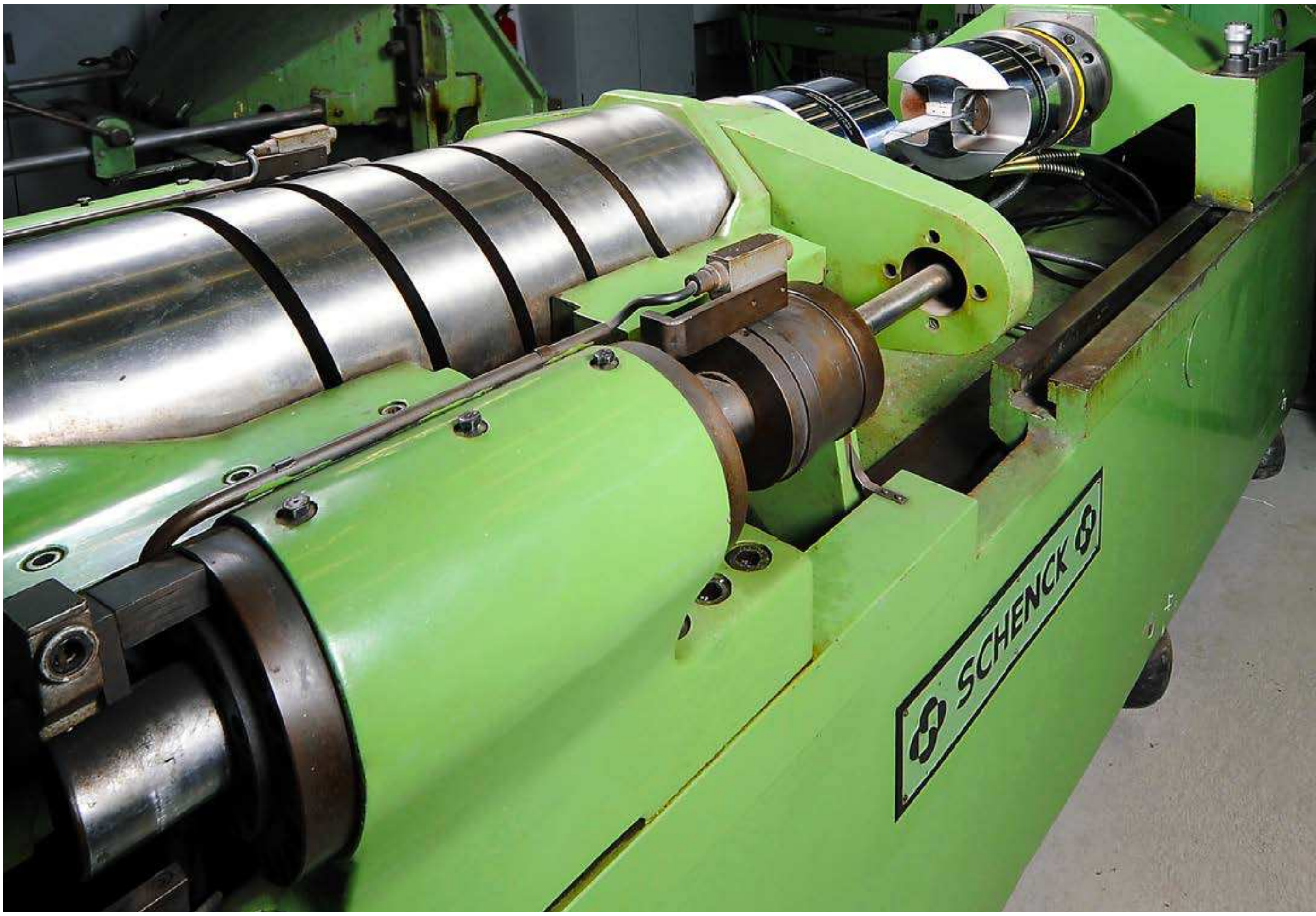


Figure 16 – FAT classes for thermal cut edge specimens



Resonance Testing Machine at TUHH

3.2.4 Summary

The main outcome of the project is that the current GL rules are suitable for fatigue assessment and design, according to the GL rules, are on the safe side. The picture for butt welds and plate edges is as follows:

Butt welds:

- Heterogeneous picture
- Effective UP treatment leads to shift of crack initiation from weld toe and root to other crack initiation points; here significant life extension has been found
- Non-effective UP treatment does not influence crack initiation point or lifetime expectation
- Quality assurance of UP treatment is a challenging task
- Non-destructive testing method for UP treatment is needed
- Qualification standards for workers performing UP treatment is needed (similar to welders qualification)
- Investigation gives an idea of the treatment effect, but due to limited number of specimens further investigations are recommended

Plate edges:

- Results sensitive to evaluation procedure (fixed / free slope)
- High-quality post-treated cut edges show increased fatigue strength compared to rule values
- Therefore, a new FAT class 150 was introduced into the GL rules in 2010
- Unexpectedly effect of 1C and 2R grinding is nearly the same
- Effect of corner treatment is more distinct than effect of complete surface treatment
- However, 2R treatment is recommended due to large in-service experience; also a good coating requires edges with radii

3.3

Fracture mechanics properties of YP47 welds [5]

3.3.1 Abstract

Within this JDP, the quasi-static fracture toughness as well as the cyclic crack propagation properties of high-toughness FCAW butt weld joints made of YP47 steel have been determined by means of an extensive test programme. Compared to the standard values given by the related rules and guidelines, the test results showed substantially more beneficial values in respect to both the fracture toughness and the cyclic crack propagation behaviour. Complemented by investigations of the residual stresses and their redistribution due to cyclic loads, a possible design variant for YP47 thick plate application in large containerships is proposed. Here in particular the application of the individual fracture mechanics properties of high toughness welds was found to be the key for fulfilling the high safety requirements.

3.3.2 Introduction

The increase in the size of containerships, which could be observed over the past years, is accompanied by an increase of the applied plate thicknesses in combination with the use of high-tensile steel. Plate thicknesses of the longitudinal members of up to 80 mm for YP47 and 100 mm for YP40 respectively reflect the current state of this development for vessels with a loading capacity of more than 18,000 TEU.

Concerns regarding the existing safety level of large containerships, especially in respect to brittle fracture and its arrest abilities, were raised and as a consequence several different research and development activities were initiated on the development of crack arrest concepts as well as concepts for crack initiation prevention.

Eventually, the International Association of Classification Societies (IACS) decided to establish a project team to investigate the impact of thick plates and high-tensile steels on the safety against brittle fracture of large containerships and to develop the necessary measures for ensuring the required safety level yielding to the newly unified requirement S33.

3.3.3 Test programme and main results

The test programme mainly consisted of tests aiming at the determination of cyclic and static fracture mechanics properties as well as the investigation of the influence of welding residual stresses mainly by means of welding simulations. More details are given in [5]. While the test matrix of the cyclic tests is given in Table 4 the test matrix of the static tests can be found in Table 5. A typical test set-up of the static fracture toughness tests is shown in Figure 17.

TABLE 4: TEST MATRIX OF THE CYCLIC TESTS

	Series A			Series B		
Condition	**as welded**			**stress relieved**		
Stress ratio R	+0.1	+0.3	+0.5	+0.1	+0.3	+0.5
No. of tests	10	5	5	10	7	13

TABLE 5: FRACTURE TOUGHNESS TEST PROGRAMME

Type	Dimensions	Series	B [mm]	T_Range [°C]	No. of tests
I	B x B	1	76	-20 / +23	12
		2	76	-60 / +23	10
II	B x 2B	1	60	-90 / +25	14
		2	75	-90 / -10	10

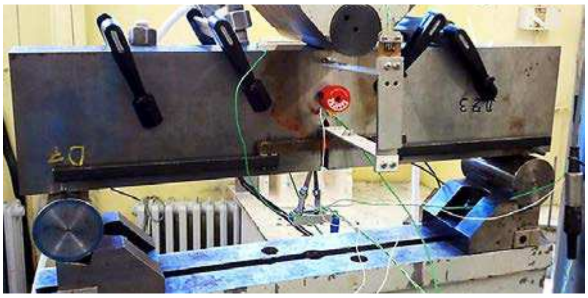


Figure 17 – Test set-up for fracture toughness tests

As a main result of the project, it was possible to establish a unique technical background for the appertaining safety concept of the GL rules and furthermore to individually adjust the related requirements. Some of the main results and findings, especially in comparison to the standard fracture mechanics parameters and procedures from common rules and guidelines, are summarised in Figure 18.

3.3.4 Summary

The main outcome of the project can be summarised as follows:

- The individual fracture mechanics properties of high-toughness butt weld joints of YP47 steel have been investigated by means of an extensive test programme
- The double master curve concept was verified and confirmed
- The results showed large differences compared to the standard properties given in the related guidelines and recommendations for fracture mechanics calculations which yield to unreasonably conservative results
- The impact of high-toughness welds of YP47 steel on the design of large containerships was investigated; based on the appertaining individual fracture mechanics properties, a design concept was derived providing the required safety levels and design life times
- Furthermore, the residual stress state for multi-pass butt joints welded under constrained conditions was investigated
- A significant redistribution and decrease was observed after cyclic loading; as a result, it was possible to propose average residual stresses for application within fracture assessment procedures

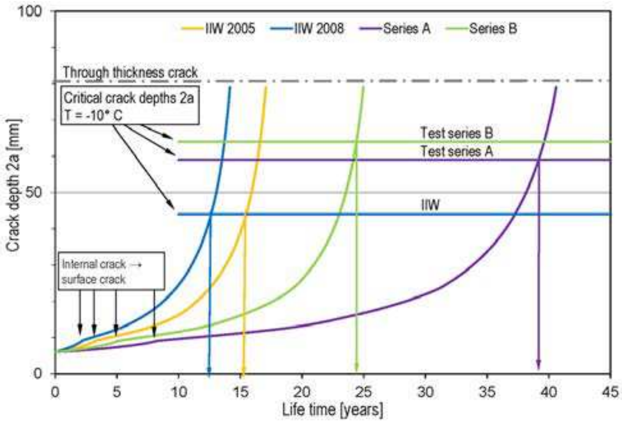


Figure 18 – Impact of different fracture mechanics properties on the calculated lifetimes

3.4

Spectral analysis [6]

3.4.1 Abstract

For simulation of fatigue damage based on first principles, the stochastic nature of fatigue load cycles requires the application of stochastic numerical algorithms. Commonly, the spectral method is used for that. But applying it to whole ships is expensive to carry out in practice and has not become a standard tool. The project identified considerable optimization potential and applied it to a tool chain based on DNV GL's ShipLoad software. The resulting software tool demonstrated that fatigue assessments with spectral methods can be performed economically for whole ship structures, requiring similar user effort and computation time as classic (design load) methods.

3.4.2 Introduction

First, principle fatigue assessment methods for ship structures, based on long-term statistics of stress spectra obtained by means of finite element analysis, have been described in the literature for at least two decades now. Despite their theoretical advantages, such methods are hardly applied in practice.

One reason for being hardly applied is the complexity of the required software tool chain. Even for a very basic spectral fatigue assessment, several rather different processing steps need to be performed:

- Selecting loading conditions and modelling associated finite element (e.g. container stacks, tank contents, bulk cargo)
- Specifying a large set of regular waves (several hundred to a few thousand) and performing a related see-keeping analysis, resulting in external pressure loads and ship motions
- Combining pressure and motion results (from the see-keeping analysis) with inertia loads (from mass modelling) and generating associated finite element load cases
- Solving the finite element equations and computing the associated stress results for a large number of load cases and elements
- Spectral/statistic post-processing of the raw finite element stresses, yielding stress spectra and fatigue results related to a large number of different sea states, ship speeds and loading conditions
- Combining all (short-term) statistic results into single (long-term) statistic results

Standard software tools are available for performing all the above process steps. But most of those standard tools have not been designed for interworking and are controlled by incompatible interfaces. Furthermore, the different tools relate to different areas (e.g. hydrodynamics, finite element simulation, fatigue assessment) of analysis that are traditionally carried out by different experts. In practice, using such a tool chain requires a large amount of expert knowledge, is error-prone and consumes a considerable amount of working time. Furthermore, the method is rather computation-intensive and easily constrained by available computer resources.

A theoretical analysis of current spectral fatigue tool chains identified significant optimisation potential. It suggested that by exploiting that optimisation potential, practical problems in managing the tool chain could be eliminated and computational efficiency could be enhanced significantly.

The identified optimisation techniques were applied to a tool chain based on the DNV GL's ShipLoad software. The modelling and management tasks occurring in a spectral fatigue assessment process could be directly supported by ShipLoad in a similar manner to a design load modelling process. A special spectral fatigue assessment module, exploiting the identified optimisation potential, was developed.

3.4.3 Main results

The software has been successfully applied within several projects, for external clients as well as for in-house rule development. As ShipLoad already supports the computation of section loads from combined hydrodynamic and internal loads, spectral analysis could also be applied to the section load values. Spectrally analysing all section load values required no additional modelling effort and was as fast as determining design loads. The additional modelling and management effort, as required from the user, for performing a spectral fatigue analysis of the finite element stresses has also been reduced significantly. Computational speed allowed performing spectral analysis for some thousand different locations and three loading conditions within a few minutes.

As an example, Figure 19 shows the influence of different operational areas on the long-term distribution of deck longitudinal stress ranges of a tanker.

Storage requirements for the spectral method were significantly higher than for design loads. But the additional storage is easily provided by modern hardware and operating systems.

3.4.4 Summary

Within the project, the spectral analysis process has been significantly optimised and the programme chain based on DNV GL's ShipLoad software has been developed into a powerful tool. Thus, spectral fatigue analysis for a very large number of FEM stress results (e.g. all elements of a global finite element model) becomes a practicable alternative to classic design loads approaches.

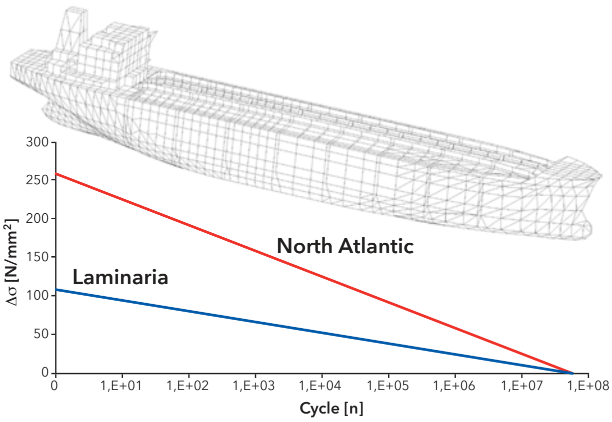


Figure 19 – Spectra of deck longitudinal stress ranges

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