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Development of Toughness and Quality Requirements for YP47 Steel Welds Based on Fracture Mechanics

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ABSTRACT

For current containership designs actually a new material class with minimum yield strength of 460 N/mm^2, called YP47 steel, is considered. In connection with big plate thicknesses and high static and dynamic loads at the upper hull girder area e. g. the coaming and the coaming top plate brittle fracture is a factor which has to be deeply investigated. This paper describes development of a safety concept based on a brittle fracture avoidance strategy using fracture mechanics methods. Finally, this safety concept results in toughness and quality requirements, which are practically applicable in shipbuilding industry. Effects of different influence parameters are discussed, such as design temperature, fracture toughness, initial defect size, and shape of load spectra. Furthermore, prospective inspection and assessment strategies are presented.

KEY WORDS: High tensile steel; fracture assessment; two criteria approach; cyclic crack growth; toughness requirements; inspection strategy.

INTRODUCTION

Mainly driven by economy of scale, the size especially of containerships increased during the past years. This development is accompanied by using steels of increased plate thickness up to 85 and even 100 mm in some cases and higher yield strength exceeding 390 N/mm^2.

Currently, a new material class with a nominal yield strength of 460 N/mm^2, called YP47 steel, is considered for latest containership designs. This development is mainly driven to reduce the plate thickness to gain the benefit of thinner plate thickness and to reduce welding work. It is the challenge for classification societies to consider all point of views and to ensure a safe application of this new material.

Actually plate thickness up to 80 mm is designated in conjunction with this material. By utilizing the higher static load carrying capacity of the material, it is intended to achieve a limitation of the plate thickness. Otherwise, utilization of high permissible static loads results also in high dynamic loads. As a typical example where the application of YP47 steel comes into consideration, a 13,000 TEU containership is shown in Fig. 1.

The main area of application for YP47 steel is the upper hull girder area, e. g., the coaming and the coaming top plate of large containerships. The characteristic high tensile loads in this area in combination with large plate thicknesses and high strength steel rises the possibility of brittle fracture. It is well known that fracture toughness decreases with increasing plate thickness, especially for steels of simultaneously increased material strength. In comparison to mild steels the so called thickness influence becomes already effective at smaller plate thicknesses, Sandsträm et al. (2005).

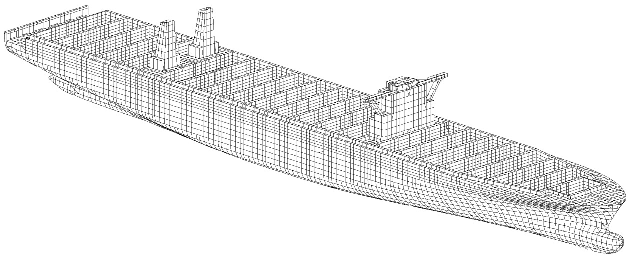

Fig. 1: Finite element model of a 13,000 TEU containership

To ensure safe operation during the lifetime of the ship it was necessary to establish a safety concept for the new material class of YP47 steel. Based on fracture mechanics calculations, this safety concept finally results in toughness and quality requirements suitable for practical application in the shipbuilding industry.

Beside the danger of brittle fracture, the danger of fatigue damages also rises for YP47 steel. This is mainly due to high cyclic loads and pronounced fatigue sensitivity of welded joints of thick high strength steel. But this paper is focused exclusively on the avoidance of brittle fracture.

SAFETY CONCEPT

Basically, within a safety concept for the avoidance of brittle fracture, the priority can be the avoidance of crack initiation or to the guarantee of crack arrest. The supplementary rules for application of YP47 steel of Germanischer Lloyd (2009) are based on a crack initiation concept. This means that the initiation of a brittle crack is excluded for the given boundary conditions. Due to uncertainties regarding crack arrest behavior, especially in ship structures under realistic boundary conditions, crack arrest is considered as a second line of defense only. Nevertheless, recommendations for a crack arrest design are given.

From the production point of view, most of these design features, e. g., shift of the block weld at the coaming, are undesired.

Typically, a safety concept for the avoidance of brittle fracture consists of different parts linked closely together. When optimizing the concept, it has to be considered that changing one parameter will effect all other parameters. The different parts and steps of a safety concept based on the avoidance of brittle crack initiation are given below:

- Determination of acceptable initial defect sizes with respect to the NDT possibilities
- Calculation of cyclic crack growth
- Determination of the critical crack size
- Comparison between the critical crack size and the size of the grown initial cracks after a certain time period
- Determination of a suitable inspection strategy

With respect to the acceptance of such a safety concept in the practical design process, a fine tuning of the above and the related parameters is one of the most important tasks. Due to the accumulation of geometrical and metallurgical notches as well as the appearance of residual stresses as additional loadings, the investigations focus on welded joints.

Finally as a condensed result of all the fracture mechanic calculations and other investigations related to the safety concept, toughness requirements, acceptable defect sizes, NDT requirements and inspection intervals will be given in rules and recommendations, e. g. Germanischer Lloyd 2009. The set up of these linked parameters is not a one step deterministic calculation, but a multi step optimization process resulting in an optimized compromise of all the parameters.

All fracture mechanics calculations presented in this paper were carried out with the software Fraunhofer IWM Verb 8.0. For fracture mechanics calculations, all internal defects were idealized as elliptical cracks and all surface defects were assumed to be semi-elliptical. A plate with a breadth of 2000 mm and a thickness of 80 mm was chosen as the geometry model for the fracture mechanics investigations. At the upper hull girder the effect of a drecrease of the section modulus caused by the loss of area due to the assumed cracks has to be investigated. For the calculations presented here this effect has been relatively small and is covered by the safety concept.

Initial Defects

To determine acceptable initial defect sizes, different mostly oppositional influences can be observed. The safe detectability of defects equal to or bigger than the acceptable defects, which is directly connected with the NDT possibilities, is essential. To minimize the need for repairs a maximization of the acceptable defect sizes is aspired.

In addition to economical aspects it has to be mentioned that the repair of a welded joint has negative influences on the mechanical properties. Contrary to this, the aspired design life time, which has to be proven, as well as preferably long inspection intervals lead to acceptable defect sizes as small as possible. Finally, this leads to a balanced compromise for the definition of acceptable defect sizes. Table 1 shows the acceptable internal defect sizes in a direction parallel to the weld seam according to Germanischer Lloyd (2009).

Table 1. Acceptable initial defect sizes (repair limit values)

No. of defects per meter	Registration Length [mm]	Max. perm. excess echo height [db]	Corresponding depth [mm]
10	10	6	6
3	20	6	6
1	10	12	8

Cyclic Crack Growth

Maximum acceptable defect sizes were used as initial cracks for crack propagation calculation under cyclic loading conditions. Crack growth calculations were carried out with the Paris law, Eq. 1. According to the recommendations of IIW (2005) the material parameters $C = 1.58 \cdot 10^{-11}$ and $m = 3$ were applied. In a conservative way, a threshold value of $\Delta K_{TH} = 4$ MPam$^{1/2}$ was assumed.

$$\frac{da}{dN} = C \cdot \Delta K^{m} \qquad (1)$$

For crack growth calculations a straight line distribution (Weibull factor 1.0) was chosen as load spectrum (spectrum A from Germanischer Lloyd, 2008). This is typical for seaway induced loads which are relevant for the primary application area in the upper hull girder of container vessels. On the basis of GL's experience from numerous strength analysis of container vessels, the maximum stress range was set to $\Delta\sigma_{max}$ = 240 N/mm^2, corresponding to 85 % of maximum permissible static stress according to Germanischer Lloyd (2008).

By means of comprehensive fracture mechanics investigations of the defects given in Table 1, the defect with the dimensions 2a/2c = 6/20 mm turned out to be significant. Hence all calculations shown in this paper contain this defect as the initial crack.

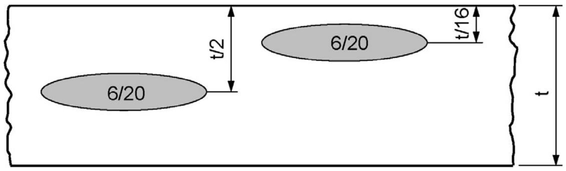

Fig. 2: Thickness positions of initial defects

The position of the initial defect in thickness direction has an important influence on the crack growth behavior and therefore on the fracture behavior. Figure 2 shows two different thickness positions, centered at t/2 and close to the surface at t/16 of the initial defects investigated in this paper. The cyclic crack growth of the centric crack and the crack close to the surface is shown in Figs. 4 and 5, respectively. The former shows a relatively small crack growth during the aspired life time of 20 years and remains as an internal crack. The latter shows a more accelerated growth behavior and breaks the surface after approximately 4 years and continues growing as a surface crack before the crack turns into a through crack after approximately 17.5 years. As seen in Fig. 5, even without consideration of the critical crack sizes, the aspired life time of 20 years could not be reached if the initial defect is located close to the surface. Therefore special focus has to be laid on the avoidance of these defects during newbuilding period.

Fracture Assessment

A two-criteria approach in combination with a limit curve according to the European SINTAP (1999) procedure is used for the fracture assessment and the determination of critical crack sizes respectively. A detailed description of the SINTAP procedure can be found in Ainsworth et al. (2001). With the help of two-criteria approaches it is possible to consider plastic loadings without expensive elastic-plastic calculations. The fracture assessment is carried out by means of an assessment point that results from the ligament plasticity Lr and the crack tip loading Kr. Usually, the failure assessment diagram (FAD) option is chosen for the assessment. Figure 3 shows an assessment point in the FAD. Assessment points below the limit curve are "safe" while assessment points above the limit curve are "unsafe". This means that crack initiation can be expected for a "critical" assessment point located directly on the limit curve.

For the determination of the critical crack sizes the maximum permissible (static) design stresses have to be applied as load induced primary stresses, σ_{pri}. Welding residual stresses have to be considered as secondary stresses σ_{sec} that effect the crack tip loading but not the plasticity of the ligament. Based on the permissible static stress for YP47 steel according to Germanischer Lloyd (2008), $\sigma_{pri} = 282$ N/mm^2 has been used as primary stress for the calculations. The secondary welding residual stress has been conservatively assumed as $\sigma_{sec} = 178$ N/mm^2 distributed constantly over the plate thickness. This results in a total stress, σ_{tot}, for the fracture assessment equal to the nominal yield strength of the material, Eq. 2.

$$\sigma_{tot} = \sigma_{pri} + \sigma_{sec} = R_{eH} = 460\,\mathrm{N/mm^2} \qquad (2)$$

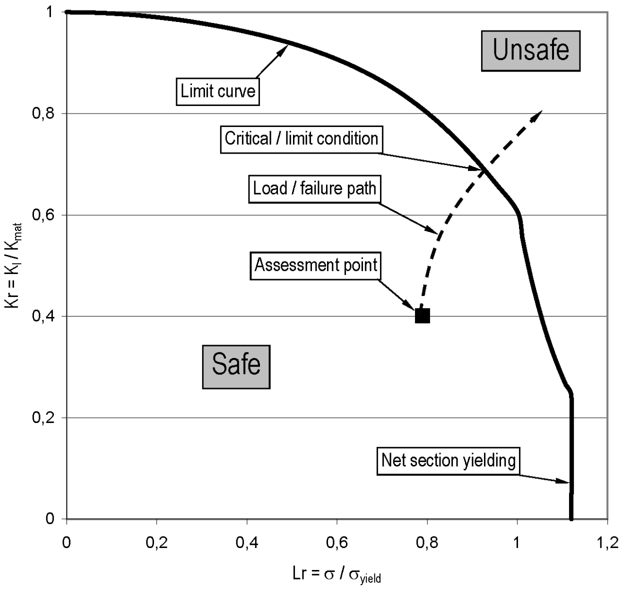

Fig. 3: FAD diagram

Beside the loadings the critical crack size is mainly influenced by the crack resistance parameter K_{mat} of the material. In the brittle region K_{mat} is equal to the fracture toughness K_{IC} while in the transition and ductile region K_{mat} describes the resistance against crack initiation (SINTAP, 1999). Modern high performance steels such as YP47 and their welds are predominantly situated in the transition region at the relevant design temperatures for shipbuilding.

As a result of fracture assessment calculations critical crack sizes for internal and surface cracks are given in Figs. 4 and 5, respectively. These calculations are based on toughness requirements as given in Germanischer Lloyd (2009) and a design temperature of 0 °C. At this point it has to be clarified that these toughness requirements are the result of an optimization process employing the methods and procedures described in this paper. For the determination of the K_{mat} values from the given Charpy requirements, the double master curve concept as described below has been utilized.

Double Master Curve Concept

In practice, K_{mat} values for special materials at certain temperatures are normally not available. The determination of K_{mat} from tests, which is essential for the fracture assessment using two-criteria approaches, is currently not a standard procedure in shipbuilding practice. In this respect it has to be mentioned that the determination of K_{mat} for welded joints is much more challenging task than the determination of K_{mat} for the base material as it is needed for the aeronautical industry for example. To overcome this problem, a double master curve approach which enables the transformation of charpy toughness values KV into corresponding K_{mat} values at nearly any temperature level is applied, (Langenberg et al., 2007). Requirements for charpy toughness values KV are given in appertaining rules and guidelines. The determination of KV values from tests is a standard procedure for shipbuilding.

In a first step the given KV values have to be transformed into T_{27J} temperatures with the help of Eq. 3, where A, B, C, and m are material constants while Pf is the probability of survival. T_{27J} is the temperature related to a charpy toughness of KV = 27J.

$$KV = A + B \cdot \exp\left[C \cdot \left(T - T_{27J}\right)\right] \cdot \left(\ln \frac{1}{1 - Pf}\right)^{m} \qquad (3)$$

Equation 3 is a master curve for the charpy toughness in the transition region. For the present calculations, Pf was assumed to be 0.5, and the material constants have been set to A = 4.07, B = 25.12, C = 0.0336, and m = 0.25, [Langenberg, personal communication].

As an intermediate step the transformation of T_{27J} values into T_{100} values is carried out by applying Eq. 4. T_{100} is the temperature where K_{mat} becomes 100 MPam$^{1/2}$.

$$T_{27J} = T_{100} - 18^{\circ} \qquad (4)$$

In the final step, the well known master curve expression given in Eq. 5 according to Wallin (1999) is utilized for the determination of K_{mat}. In Eq. 5 T is the actual assessment temperature, Pf is again the probability of survival, and beff is the length of the crack front or the plate thickness, respectively. For the calculations an assessment temperature T = 0 °C was chosen. Pf was again set to 0.5. The well known effect that fracture toughness decreases with an increase of the plate thickness is considered in the master curve approach acc. to Eq. 5 by the parameter b_{eff}.

$$K_{mat} = 20 + \left[11 + 77 \cdot \exp\left\{\frac{T - T_{100}}{52}\right\}\right] \cdot \left(\frac{25}{b_{eff}}\right)^{\frac{1}{4}} \cdot \left(\ln \frac{1}{1 - Pf}\right)^{\frac{1}{4}} \qquad (5)$$

Finally, the double master curve approach presented above is the key for the practical application of fracture mechanics methods for shipbuilding industry and related rules, because it enables a safe and easy determination of individual K_{mat} values. In Table 2 examples are given for required KV values and the corresponding K_{mat} values calculated with the help of the double master curve concept.

Results

It is essential for a safety concept for the avoidance of brittle fracture to bring the results of the crack propagation calculations and the results of the fracture assessment together. In Figs. 4 and 5 the cyclic crack growth as well as the critical crack sizes for an initial crack located in the centre of the plate thickness (t/2) and close to the plate surface (t/16) are shown. While the former do not reach the critical crack size during the aspired life time, the latter becomes critical after approximately 16.2 years. This is mainly due to the accelerated crack growth of the surface crack compared to the internal crack.

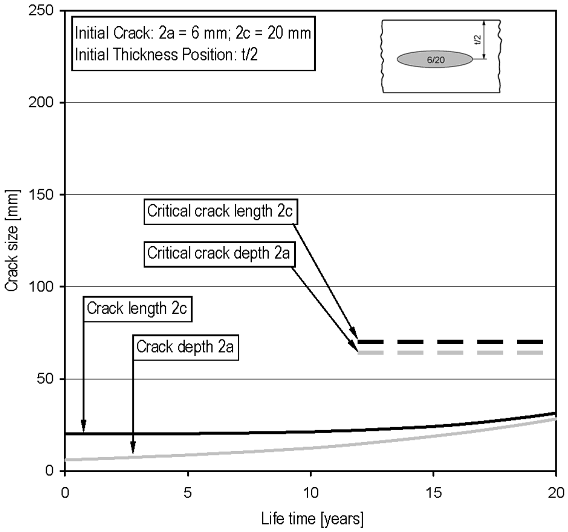

Fig. 4: Crack growth and fracture assessment of a center crack

As a consequence, the investigations have been focused on situations where the initial defects are located in areas near the surface. Parametric calculations, where the positions of the initial defects were varied systematically, have been carried out to determine a critical zone close to the surfaces. Initial defects with the maximum acceptable size of 2a = 6 mm and 2c = 20 mm, located in this zone, will not reach the aspired life time of 20 years. Conservatively, the size of this zone is approximately 25 % of the plate thickness below the surfaces.

INSPECTION STRATEGIES

When discussing inspection strategies it has to be clearly differentiated between the fatigue assessment of a structure and the saftey concept for the avoidance of brittle fracture. The latter is based on a postulated initial crack utilizing fracture mechanics methods. While the fatigue concept for YP47 steel is the same as for all other steels (Germanischer Lloyd, 2008), the development of the inspection strategy related to the safety concept for the avoidance of brittle fracte is described below (Germanischer Lloyd, 2009).

Basically, the size of an initial crack, grown under cyclic service loads, must not reach or exceed the corresponding critical crack size within the life time or inspection interval. Furthermore, it has to be ensured that a crack which is sized just below the repair or NDT limits for inspections does not become critical during the following inspection interval or better during the next two inspection intervals.

From fracture mechanics calculations, it is obvious that, for the given boundary conditions, the aspired life time in shipbuilding industry 20 or sometimes even 25 years can not be reached calculatory without in-service inspections for defects located in the critical surface zone (see Fig. 5).

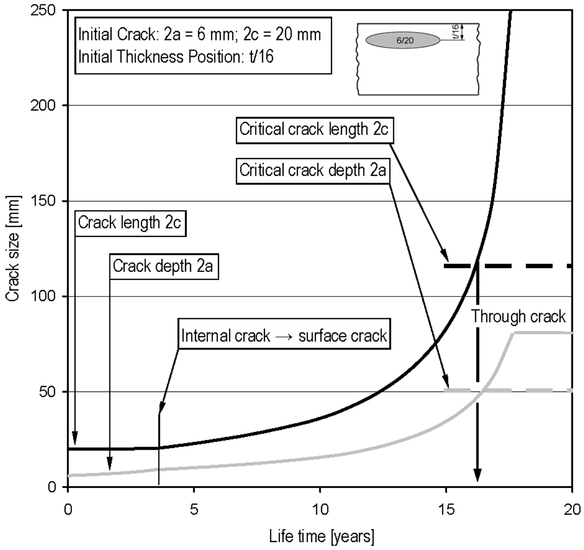

Fig. 5: Crack growth and fracture assessment of a near-surface defect

The situation becomes even worse if the coalescence of neighboring defects located near the surface is taken into account. This situation is shown schematically in Fig. 6.

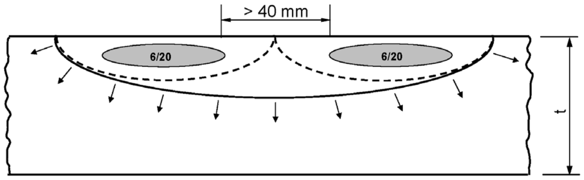

Fig. 6: Coalescence of two near-surface defects (schematically)

Under consideration of the minimum tolerable distance of 40 mm between two adjacent defects according to Germanischer Lloyd (2009), the maximum length of the corresponding surface cracks is limited to 2c = 60 mm, so as to avoid the coalescence of these cracks. Figure 7 shows the coalescence of two near-surface defects in the fusion zone of a butt weld of an 80 mm thick plate.

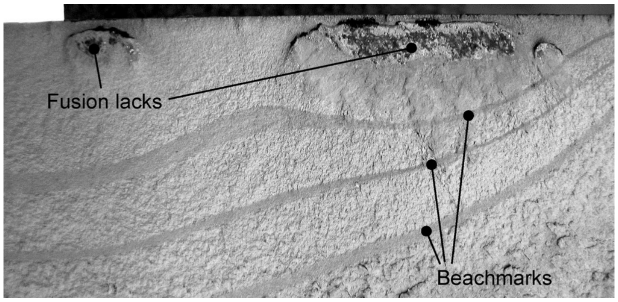

Fig. 7: Coalescence of two adjacent near-surface defects in a butt weld

As can be seen in Fig. 8, the calculated life time is reduced to approximately 14.5 years if the coalescence of two adjacent near-surface cracks is considered. Within the fracture mechanics calculations the process of coalescence is simulated by an abrupt step of the crack length. The crack depth is assumed to remain constant. This results in an accelerated crack growth for both crack length and crack depth, see Fig. 8. In order to enable a good comparison between the situation with and without coalescence, the latter situation is also included in Fig. 8 as light gray curves.

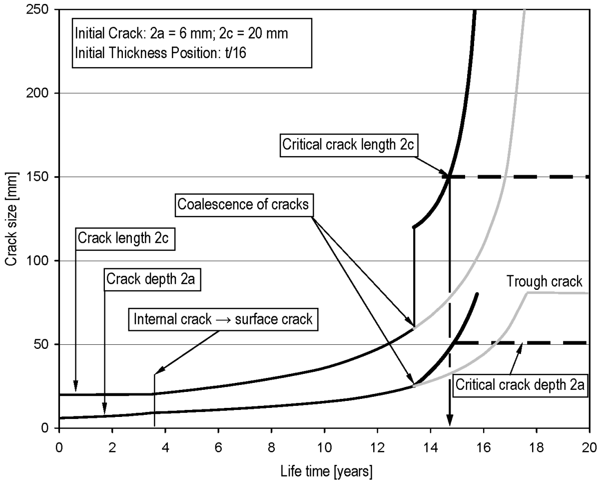

Fig. 8: Crack growth and fracture assessment under consideration of coalescence of adjacent near-surface defects

Furthermore, the investigations showed that for defects located outside the critical surface zone, e.g., adjacent defects located in the plate center, the danger of coalescence does not exists. This is due to the relatively small crack growth of these internal cracks, see also Fig. 4.

As already mentioned fracture mechanics calculations show that for near-surface defects a life time of 20 or sometimes even 25 years, that is normally aspired in shipbuilding, could not be guaranteed without in-service inspections. An adjustment of the boundary conditions, e. g., reduction of acceptable initial defect sizes or enlargement of the distance between adjacent defects seems not to be useful in this context. Both measures would lead to a significant increase of the rectification work of the butt welds by gouging and rewelding with all its negative implications. Furthermore the influence of an enlargement of the minimum distance between adjacent cracks would have only a small influence on the life time due to the strong accelerated crack growth for crack length greater than 50 mm. On the other hand a reduction of the acceptable defect sizes the NDT limits regarding a safe detection would be reached or exceeded.

The need to prove the proper condition of a structure by means of in-service inspections marks a new situation for the shipbuilding industry. Indeed, the condition of the ship structure was also deeply checked during class renewals every five years so far e. g. by visual inspection and thickness measurement, to record the corrosion state and to replace structural components if necessary. As far as fatigue is concerned structural details have been designed and proven for the complete life time without any inspection.

Regarding the safety concept for the avoidance of brittle fracture of YP47 welded structures, this is completely different. The proof of the proper condition of the structure that has to be achieved is mandatory on the basis of the design. This results in renunciation from the traditional life cycle design towards an inspection based design, as it was already successfully established in other industries, such as the aircraft industry, for example, for areas showing high dynamic loads. Considering the results of the fracture mechanic calculations presented here, an inspection interval of five years starting from ten years life time seems to be suitable for the in-service inspection of thick plate YP47 welds in high loaded areas. The magnetic particle method as well as visual inspection will be applied for the detection of surface cracks.. For a periodic five year inspection interval the inspections can be performed during the normal five year class renewal. In this way additional service interruption can be excluded or minimized.

Influence Parameters

The safety concept for the avoidance of brittle fracture presented in this paper consists of many different parts and is influenced by many different influence parameters. Some of these will be discussed in the following parts.

Fracture Toughness Requirements

One possibility to optimize (enlarge) the needed inspection intervals is to tighten the toughness requirements. This will increase the critical crack sizes and, therefore, the life time too. Table 2 shows the effect on the life time if the toughness requirements are varied. Coalescence of adjacent defects has not been considered in these calculations. As a start point the present toughness requirements of KV = 57 J at -20 °C according to Germanischer Lloyd (2009) have been used. Afterwards, the effect of increased fracture toughness has been investigated by decreasing the corresponding prove temperature.

Table 2: Influence of toughness requirements on the life time

Charpy toughness	K_{mat} [MPam$^{0.5}$]	Life time [years]
57 J at -20 °C	204	≈ 16.2
57 J at -40 °C	286	≈ 16.9
57 J at -60 °C	408	≈ 17.5

Due to the high crack growth rates of relatively large cracks even an increase of fracture toughness by 100 % gains only to an enlargement of the life time by 8 %. So the toughness seems not to be the favourable parameter to modify for an extension of the inspection intervals. On the other hand, it is not allowed to decrease the toughness requirements, taking into account a certain reduction of the safety margin related to the inspection intervals. Adequate toughness requirements are essential to ensure a sufficient safety level of a structure. In this context it should be mentioned that the avoidance of brittle fracture initiation is not the only design criterion.

Crack Growth Parameters

It can be presumed that the crack growth parameters of the Paris law C and m acc. to IIW (2005) are conservative due to their wide range of application. Generally they are valid for all types of welded joints at ferritic steels and have to ensure a safe assessment for all of them. For a high quality weld of modern high performance steel this may lead to conservative results.

In order to investigate the influence of changing the crack propagation parameters, it was assumed that the parameter C of the Paris law is decreased by 10 % to $C = 1.42 \cdot 10^{-11}$. A deviation of 10 % from the value given in IIW (2005) seems to be a realistic magnitude achievable by testing. This results in a life time that is increased by 10 % from approximately 16 to 18 years. So an adjustment of the crack propagation parameters of the Paris law seems to be a promising and suitable way to optimize inspection intervals.

Shape of Load Spectrum

From Figs. 5 and 8 it becomes obvious that the achievable life time is mainly influenced by the parameters describing the cyclic crack growth. This is confirmed by the investigations of the influence of the toughness requirements. In this respect the shape of the load spectrum is a very sensitive parameter.

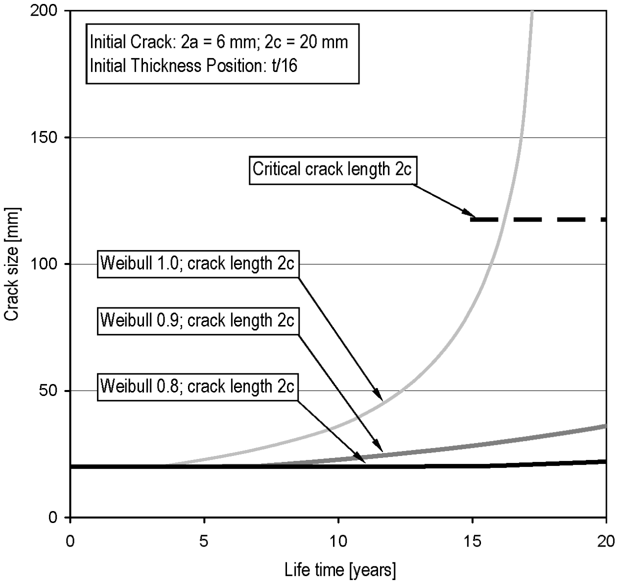

Fig. 9: Influence of the load spectrum shape on life time

Figure 9 shows the crack growth and fracture behaviour of a near-surface defect if three different load spectra are applied. The spectra have the same range of $5 \cdot 10^7$ load cycles but different shapes, expressed by Weibull factors of 1.0, 0.9 and 0.8. A Weibull factor of 1.0 corresponds to a straight line spectrum as it is typical for seaway induced loads based on the North Atlantic wave climate. In contrast to this the Europe – East Asia sailing route, typical especially for large containerships, shows a Weibull factor of approximately 0.8 (von Selle et al., 2001).

As is can be seen in Fig. 9, the influence of spectrum shape on crack propagation and, therefore, on the achieved life time is essential. However, an utilisation of the associated benefits is not possible because this would require a limitation of the sailing area of the affected ships. This is neither designated by the owners nor can this be proven in practice under current boundary conditions.

CONCLUSIONS

With the help of fracture mechanics calculations, a safety concept for the avoidance of brittle fracture in YP47 welds was established. For practical application the fracture mechanic basis of the concept has been transferred into toughness and quality requirements by means of a double master curve concept.

It was shown that in-service inspections with an inspection interval of five years starting from ten years life time are mandatory for near surface defects. For the shipbuilding industry this means a shift from “Life Cycle design” towards “Inspection Based design”. A design philosophy that is established in the aeronautical or the nuclear power industry for many years. An adjustment of the concept based on different detail investigations will be a task for the future.

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