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Proper repair of failure for ship structural connections

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After a new ship is delivered, the ship's hull structure must be monitored by a series of internal and external inspections to assess the integrity of the ship structures. These inspections provide means to evaluate the current condition of steel and coatings and to detect unexpected damages. During an inspection, several types of structural failures can be found. Fatigue cracks, corrosion and buckling are the most common failures. When a structural failure in the form of cracking is discovered, a decision must be made as to the most effective repair. This decision is difficult due to the vast array of engineering, construction and repair knowledge. Three types of repairs namely; crack repair, steel renewal and steel reinforcement are considered. The aim of this paper is to select the proper repair of failure for critical structural connections and to estimate the repair life on the basis of fatigue strength only. Four models of alternatives repair are analyzing using FEM to determine variation of stress reduction factor. After that the repairing life is estimated for each model. The effect of residual stresses and plate imperfections is taken into account.

إصلاح الوصلات من المهام الصعبة التي تواجه مشاكل بناء السفن .الكشف على بدن السفينة في المراحل الأولية قد يؤدي إلى اكتشاف وجود كسور في الوصلات الإنشائية. تحديد الطريقة المثلى للإصلاح من أصعب القرارات وذلك نتيجة وجود عوامل كثيرة لتحديد أنسب طرق الإصلاح. ثلاثة أنواع من إصلاح الوصلات سوف نقوم بدراستها على سبيل المثال تنظيف الوصلة ولحامها و استبدال اللوح أو تقوية الوصلة. تحديد أنسب الاختيارات سوف يرجع إلى حساب مقاومة التعب لكل طريقة وذلك بواسطة استخدام طريقة الوحدة المحددة.اخذ في الاعتبار عند حساب مقاومة التعب تأثير الاجهادات المتبقية وتشوهات الألواح والمقويات.

Keywords: Ship structural failures, Repair, FEM, Fatigue strength, Ship structural connections

1. Introduction

A ship structure may be classified into categories, ranging from global to detailed structure. The global hull can be simplified as a beam. To ensure this beam has sufficient longitudinal strength, the midship section modulus must be properly evaluated during the design stage. The local strength of the structural connections must also be determined. Generally, it is not possible to completely analyze all the structural connections to determine their fatigue strength. As a result, structural analysis is performed for critical structural details such as longitudinal cutouts and beam brackets, which have high failure records [1].

Cracks are potentially the most serious defects as they can grow rapidly leaving affected structures unable to bear loads [2]. As a result of a crack, the structure around the crack will carry a greater loading that may in turn lead to its failure. If this cracking process continues unchecked, hull girder or plate panels can collapse. As a result, the ship structure has to be inspected periodically and repaired as warranted. Ship structure connections can be grouped into two types according to their importance in structural strength. Primary structure is the structure, which contributes to the main ship structural strength. Secondary structure is the structure, which neither contributes to ship structural strength nor the watertight integrity [3].

In this paper repair life for cracked longitudinal–transverse intersection representing a structural connection in an existing ship is studied. Different repair alternatives for the connection are discussed [4]. It is difficult to decide which proper repair is most reliable and cost effective for a particular crack. The selection of different repair alternatives depends on the location of crack and the expected life of the ship. A comparative analysis is proposed to estimate the fatigue lives of the repair alternatives. Four models of alternatives repair are analyzing using FEM to determine variation of stress reduction factor. After that the repairing life is estimated for each model. Several considerations are discussed including fatigue damage factor, stress concentration factor and initial imperfections of structural connections.

2. Repair alternatives for longitudinal cutout

The crack repair for a longitudinal cutout is a difficult and demanding task for ship owners. There is no reasonable consensus on what, how and when to repair. Three types of repairs, crack repair, steel renewal due to corrosion and grooving repair are common in ship structures. In this paper only crack repairs is discussed [5].

Cracks are potentially the most serious of defects as they can grow rapidly in size leaving affected structure unable to bear loads. As a result, the surrounding structure will carry a greater loading that may lead to its failure. If this process continues unchecked, hull girder or long panel will collapse. Repairs of cracks vary widely. Repair of cracks can range from temporary patches to stop leaks to complete re-design of the structural connection and replacement of steel nearby the connection. Welding cracks is a popular repair, but it frequently failed again within a short time. Repairs of these cracks can range from simple welding to addition of reinforcing elements. Cracks in primary structure require more serious repair than those in secondary structure. Cracks in primary structure may be temporarily repaired by fitting double plates or gouging out the crack and filling in with weld metal. Gouging and re-welding is an easy and common way of repair. However, the strength of re-welded cracks is usually less than the original one. The repaired weld will create new crack potentials and may fail even earlier. The better and formal ways of repair are to crop and renew the cracked plate or to modify the local geometry to reduce the stress concentration. If a longer life continuance is expected for the ship, a more robust repair such as geometry modification should be considered. The general strategies for crack repair of critical structural connections can be classified in the following way [6].

1- Grind out crack and re-weld: Re-welding is an easy and common way of repair. However, the strength of re-welding cracks is worse than the original one.

2- Re-weld the cracks plus post welding improvements: This repair is basically the same as the previous one, except that the weld is ground into smooth surface to improve its fatigue strength.

3- Replace the cracking plate: The inserted new plate has a new fatigue life. If the loading history and material properties are identical to those of the failed plate, its fatigue life should be about the same as the failed time of the crack.

4- Modify designs by adding bracket, lug or collar plate: The more robust way of repair is to modify the local geometry to reduce the stress concentration. Improving the structural design can reduce the stress concentration and therefore increase the repair life as shown in figs. 1 and 2.

5- Enhance scantling in size or thickness: Increasing the size of the structural detail like a bracket is good. However increasing plate thickness may lead to discontinuity in the connection. Depending on the economic goals of the owner, a different repair alternative could be selected. For example, if the ship has only two more years in service, the cheapest alternative with an expected life of greater than two years will be selected.

3. Multi -stage finite element analysis

The loads acting on a ship are both static and dynamic. They come from the ship's structure weight, cargo, operation, environment and from her motion. The acting loads on a ship may be classified into: a) Static loads such as still water loads, all hull cargo weights and dry docking loads. b) Slowly varying loads such as wave loads, sloshing of liquid cargo, shipping of green seas on deck and other loads. c) Rapidly varying loads such as slamming, springing and forced vibration loads. More information about this load is summarized in ref. [1]. These loads are considered on three levels as follows:

1- The direct local load on plates and stiffeners.

2- Moments and shearing forces acting on the ship transverse web frames.

3-Longitudinal bending moments and shearing forces created on the hull girder as a beam.

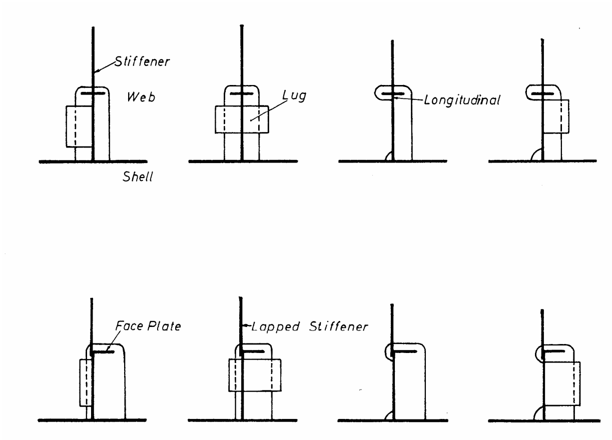

Fig. 1. Different slot arrangements.

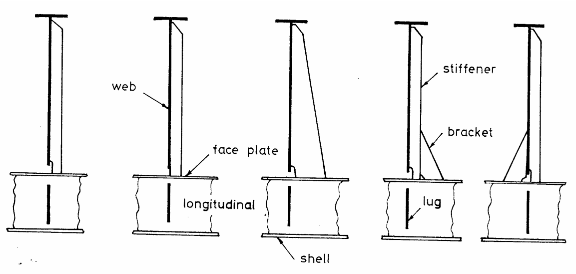

Fig. 2. Different stiffener arrangements.

According to causes of failures for ship structural details, the FEM is conducted. If the failure mode is high cycle fatigue with a high degree of certainty, then a fatigue analysis would be required. In order to obtain the hot spot stress, ideally a multi-stage FEM should be performed [7]. In this case, a global model is built to represent the overall ship hull structure. Some intermediate models are developed to represent the stiffened panels of the ship hull. The displacement of the global model can be used as boundary conditions of the intermediate model. A detailed local model is required to represent the complex geometry of the interested area. Several levels of zooming are then used while refining the FE meshes to evaluate the response of structural assemblies and individual members.

Due to the geometric singularity at the hot spot the developed stress is increased which results in the formation of a local plastic zone. A non-linear FEA is required for this analysis to clarify the stress distribution and loads transmission in the structural connections [8]. In this paper we compare hot spot stresses for different models (with repair and without repair) of the critical area to some significant loads such as pressure, longitudinal bending moment, and shear force. These loads could be estimated and applied directly to the local area.

4. Fatigue strength of repaired joints

Fatigue may be defined as a process of cycle by cycle accumulation undergoing fluctuating stresses. A significant feature of fatigue is that the load is not large enough to cause immediate failure. Instead, failure occurs after certain number of load fluctuations has occurred. Hence, damage has reached critical size. Fatigue strength of welded structures is based on SN data obtained with realistic welded specimens. The fatigue life is completely spent in the crack growth stage. Here, the crack initiation stage is unimportant in welded joint. This is because of the presence of the weld defects. Fatigue design is based on both the nominal stress and the hard spot stresses. The stress concentration caused by the welding is included in the SN curve as an implicit fatigue notch factor [9]. However, stress concentration due the overall geometry must be considered.

The design SN curve (fig. 3) is based on experiment data. The test data are obtained in high cycle region. The most important stress is the stress range, defined as the difference between a load peak and the subsequent trough. The acting stress range, S is given as;

$$S = \sigma_{avc} - \sigma_{avt}, \qquad (1)$$

where:

σ_{avt} = the average tensile stress, and

σ_{avc} = the average compressive stress.

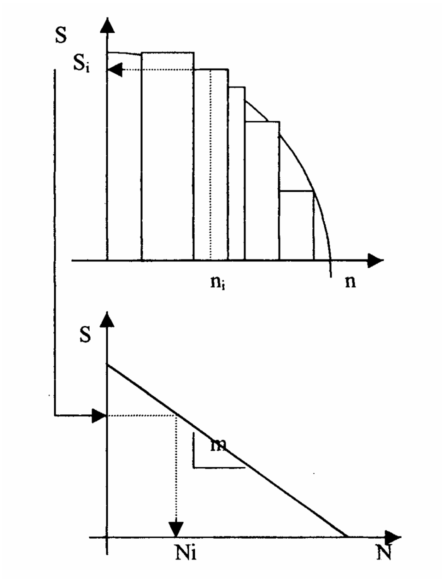

Fig. 3. Miner's rule and S-N curve interaction.

Practically, the whole stress range, S is considered if the plate panel is initially stressed with the residual stresses. The usual S-N curve equation is given as follows [10];

$$N = C\ S^{-m}, \qquad (2)$$

where:

N = The fatigue life at failure under constant stress range S(N/mm^2),

C = the value of N at the intersection of the S-N curve with the N-axis, and

m= the inverse slope of the S-N curve.

To apply eq. (2), a suitable S-N curve is obtained from ref. [10,11] similar to the structural connection. It is assumed that the S-N curve will be lowered by two classes after repairing by veeing and welding. It will be lowered by one class after repairing by veeing and welding plus post weld improvement. Inserting a plate will produce no change of S-N curve or stress level. If adding a lug or bracket, the S-N curve is lowered by two classes, however, the stress concentration factor is reduced. The reduction of stress concentration factor should be expressed in terms of the tensile stress normal to the expected direction of the crack (Mode I cracking). It is estimated as follows;

$$K_s = S_{max2} / S_{max1}, \qquad (3)$$

where:

S_{max1} = host spot stress range before repair, and

S_{max2} = host spot stress range after repair.

5. Factors influence the fatigue strength

Fatigue strength of structural elements are influenced by many factors. These factors are discussed as follows [12]:

Structural geometry: The acting stress is affected by the geometry of the section. For complicated structural connections, the net section stress may not be easily defined and the stress concentration is calculated on the basis of the nominal stress. This stress concentration can be calculated using the FEM.

Size-effect: The fatigue strength of any structural element will tend to decrease as the weld length increases. In fatigue testing, the specimen length is typically some centimeters, whereas in actual structures, each welded joint will have dimensions by meters.

Residual stress: Residual stresses exit in and close to a weld, and are self balanced over the cross section of the member. The cause of these stresses is the thermal contraction of parts of the cross section, under the restraint from cooler portions. Stresses will be large (close to the yielding point). The effect of tensile residual stress is treated as a static mean stress in the plate. This tensile residual stress will also increase the possibility of fatigue failure.

Material properties: Fatigue of structural elements is essentially a process of fatigue crack growth. Crack growth rate for steel are remarkably insensitive to material properties. Therefore fatigue strength is independent of the material yield strength.

Initial imperfections: The initial imperfections influence the stress range acting on plate panels and in particular at locations of cutout. The effect of the component of initial deflection similar to the buckling mode will increase the magnitude of the acting stress range[13].

Environment conditions: Extensive corrosion-fatigue data have been obtained for various specimens in salt water and water vapor environments. The results indicate that these environments have a significant effect on the fatigue-crack growth rate for these specimens [9]. The free corrosion environment reduces markedly the fatigue life of specimens. However, the fatigue strength could be controlled using a normal degree of cathodic protection.

6. Repair life estimation

The method of repair life estimation will vary with the mode and cause of failure. For each mode, a different analytical procedure is required. In this paper the cumulative fatigue damage model is applied. Fatigue design of welded joints is based on constant SN data. A ship structure, however, will experience a load history of stochastic nature. Miner's damage factor link between the constant load and the variable load by using the damage concept. In a stress history of several stress range S_i each with a number of cycles n_i, the damage sum may be given as follows [14,15];

$$D = \Sigma(n_i/N_i) < \Delta, \quad (4)$$

where:

Δ = The acceptable cumulative damage. Δ must be less than 1,

n_i= The number of cycles corresponding to S_i (fig. 3), and

N_i= The number of cycle to failure at S_i.

The most common way of representing irregular load histories for fatigue is by an exceedance diagram of stress range. This diagram is called the stress spectrum. In many cases, the stress spectrum can be approximated by a Weibull distribution function. Hence, the repair life, T, may be estimated as follows;

$$T = \Delta C/B^m \Omega \quad , \quad (5)$$

$$\Omega = (S_{max}{}^m/(\ln N_o)^m \, . \, \Gamma(1+m), \quad (6)$$

where:

B= uncertainty factor, and

Γ= the Gama function.

The equation implies, the Miner' rule, the SN curve and the maximum stress range S_{max} is given by;

$$S_{max} = \O\{\Delta.C/[N_o \, \Gamma(1+m)]\}^{1/m} \ \ln N_o. \quad (7)$$

where:

N_o = the total number of fatigue cycles, and

$\O$ = a factor taken into account effect of initial imperfections.

When a repair is made, the following procedure is carried out:

1- Assume N_o the life of joint at inspection when a crack is discovered.

2- Calculate the acting stress S_{max1} which causes failure using eq. (7).

3- Calculate new acting stress S_{max2} after repair alternative using eq. (3).

4- Calculate the fatigue life, T, that corresponds to S_{max2} using eq. (5).

7. Case study

There is a variety of designs of longitudinal web intersections. In this paper a longitudinal–transverse intersection representing a typical structural connection in an existing ship is studied as shown in fig. 4. The model contain one span of transverse web and longitudinal. The dimension and radius of cutout are taken from an existing ship. Different models representing proper repairs of failures for the structural connection are investigated as shown in table 1. These models are analyzed using FEM to determine the variation of Stress Reduction Factor (SRF). After that the repairing life is estimated using the previous procedure. In these analyses we calculate the stress reduction factors at radius of cutout for the given structural detail under the effect of a hydrostatic pressure. Values of stress concentration factors are shown in fig. 5.

From the results of the FEM, it was found that all structural connections have very similar stress pattern around the cutout radius for all models as shown in fig. 6. The pressure load from the sea water is transmitted from the skin plate to bear on the longitudinal. Then the load is transmitted to the web transverse, bracket and the lug plate.

In order to reduce the stress concentration in the cutout radius a lug or a bracket is added. For a model with lug the average stress concentration is reduced to 76% of its original value. For a model with bracket, the stress concentration is reduced to 66% of its original value. The stress concentration is reduced to 52% of its original value when added lug and

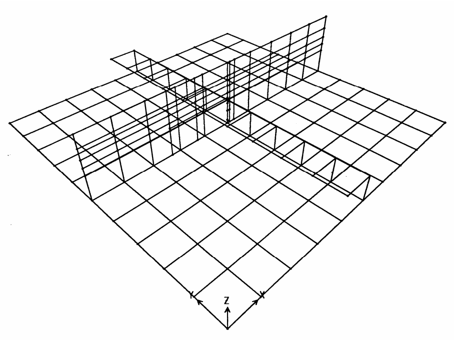

Fig. 4. FEM model of the longitudinal cutout.

Table 1
Repair alternatives for a ship structural cutout

Type of repair	S-N curve	SRF
1- Welding the crack	E-class	1.0
2- Welding + post welding	D-class	1.0
3- Insert plate	C-class	1.0
4- Welding + added Lug	E-class	0.76
5- Post welding + added Lug	D-class	0.76
6- Insert plate + added Lug	C-class	0.76
7- Welding + added T. bracket	E-class	0.66
8- Post welding + T. bracket	D-class	0.66
9- Insert plate + T. bracket	C-class	0.66
10-Welding +Lug +T. bracket	E-class	0.52
11- P. Welding +Lug +T. bracket	D-class	0.52
12- Insert plate +Lug +T. bracket	C-class	0.52

bracket to the model. The repair life is estimated for the chosen alternative repair.

Figs. 7-10 show the relationship between the life to failure and the repair life for the above four models. It is obvious from these figures that the repair lives are decreased as the lives to failure decrease. Therefore, the better and formal ways of repair are to crop and renew the cracked plate or to modify the local geometry to reduce the stress concentration. It is possible to define which repair alternative is the most reliable and cost effective for this crack.

8. Conclusions

The Repair life of longitudinal- transverse intersection representing structural connections in an existing ship is studied. Different alternatives for structural repair are discussed. A comparative analysis is proposed to estimate the fatigue lives of the repair alternatives. Several considerations are discussed

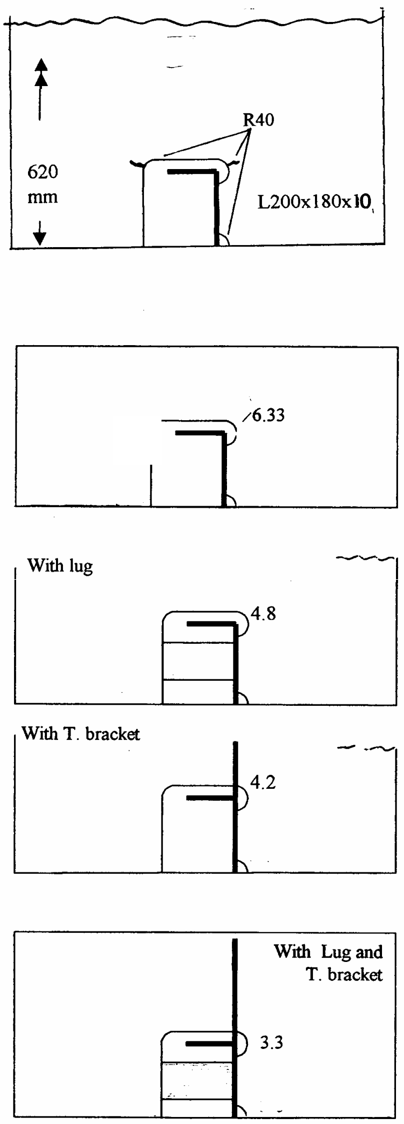

Fig. 5. Stress concentration factor at hot spots.

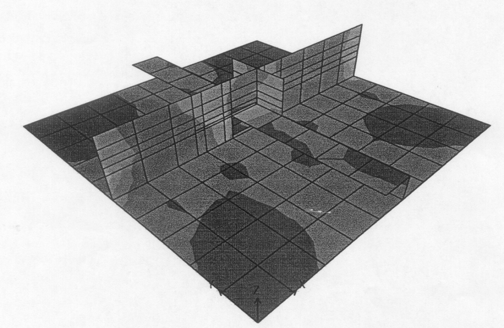

Fig. 6. Stress diagram for the model.

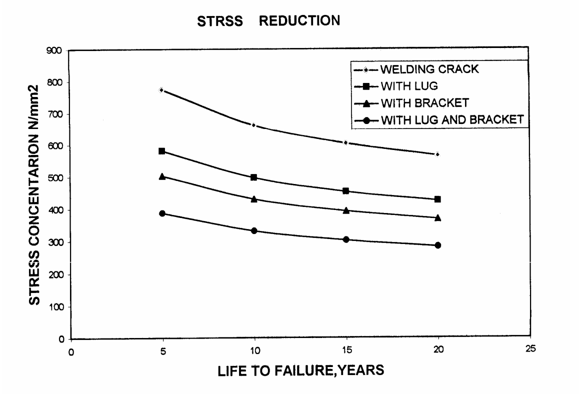

Fig. 7. Relationship between stress range and life to failure.

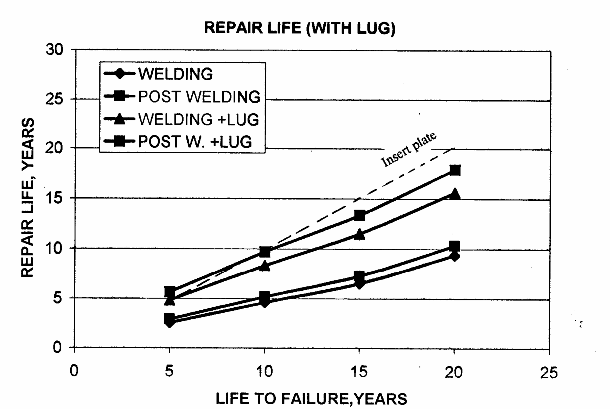

Fig. 8. Relationship between repair life and life to failure (adding LUG).

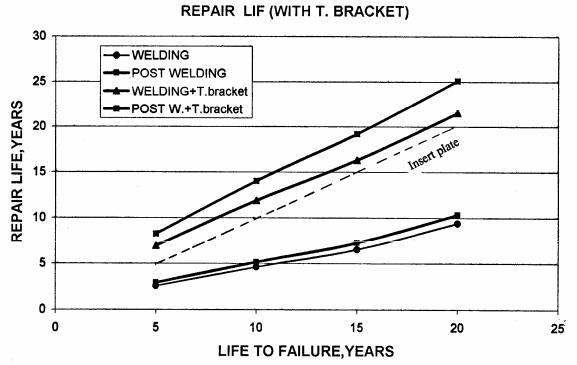

Fig. 9. Relationship between repair life and life to failure (adding bracket).

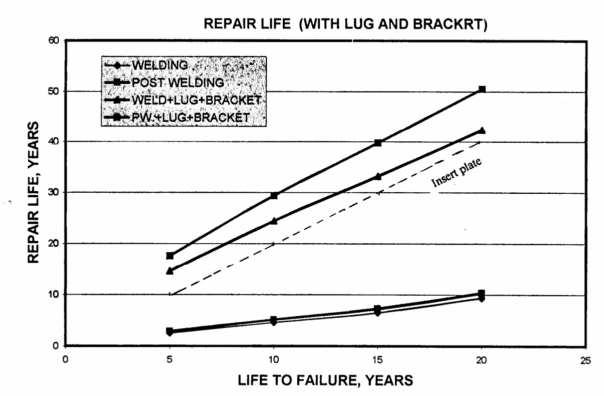

Fig. 10. Relationship between repair life and life to failure (adding bracket).

including fatigue damage factor, stress concentration factor and S-N curve. From this study, the followings are concluded:

1- The stress concentration at radius of cut-out for the given structural detail is reduced to 52% of its original value when adding a lug and bracket. However, it was found that adding of a bracket created a new hot spots in the joint.

2- The repair lives are decreased as the lives to failure decrease. Therefore, the better and formal ways of repair are to crop and renew the cracked plate or to modify the local geometry to reduce the stress concentration.

3- Economic considerations can play a dominant role in repair decisions. If a longer life continuance is expected for the ship, it is possible to define which repair alternative is the most reliable and cost effective for this crack.

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References

[1] O. Hughes, Ship Structural Design: A Rationally-Based, Computer Aided, Optimization Approach, Published by John Wiley, New York (1983).

[2] H. Kitagawa, R. Yuuki and K. Tohgo, "A Fracture Mechanics Approach to High-Cycle Fatigue Crack Growth under In-plane Biaxial Loads", Fatigue of Engineering Materials and Structures, Vol. 2 (1979).

[3] K. Tanaka, T. Hoshide, A. Yamada and S. Taira, "Fatigue Crack Propagation in Biaxial Stress Fields", Fatigue of

Engineering Materials and Structures Vol. 2 (1979).
[4] T. Stanley, Fracture and Fatigue Control in Structures: Applications of Fracture Mechanics, Prentice-Hall, Inc., NJ (1977).
[5] K. Ma and G. Bea," Repair Management System For Critical Structural Details in ships", Ship Structural Committee, pp. 1-78 (1997).
[6] A.S. Krausz, Fracture Kinetics of Crack Growth, Kluwer Academic Publishers, London (1988).
[7] A.A. El-Badan, Data Generation Techniques for Ship Structural Design analysis, A thesis submitted for PHD, University of Strathclyde, Glasgow (1975).
[8] M.A. Shama, On the Stress Distribution Around Longitudinal Cutouts, Technical Report (1970).
[9] R. Skjong, R. Torhaug, Rational Methods for Fatigue Design And Inspection Planning of Offshore Structure, "Marine Structures, Vol. 4, pp.381-406 (1991).
[10] K. Horikawa and S. Cho, "Initial Fatigue Growth Behavior in a notched Component", Trans. of JWRI (1988).
[11] A. Almar-Naess, Fatigue Handbook, Offshore Steel Structure, Published by Tapir, Norway (1885).
[12] D. Faulkner, "Effects of Residual Stresses on The Ductile Strength of Plane Welded Grillages and of Ring Stiffened Cylinders ", Journal of Strain Analysis, Vol. 12 (2) (1977).
[13] Y. Ueda, S.M.H. Rashed and Y. Abdel-Nasser, "On Buckling Accepted Design of Ship Structures Utilizing HTS" J1.of Society of Naval Architects of Japan, Vol. 171 (1992).
[14] C.G. Soares, "Model Uncertainty in the Long-Term Distribution of Wave-induced Bending Moments for Fatigue Design of Ship Structures", Marine Structures 4, pp. 295-315 (1991).
[15] M.M.A. El-Gammal, New Method For Estimating The Fatigue Life of Ship Structures", I.S.P., Vol. 22 (254) (1975).

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