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Zhejiang University is one of the leading universities in China. In *Advanced Topics in Science and Technology in China*, Zhejiang University Press and Springer jointly publish monographs by Chinese scholars and professors, as well as invited authors and editors from abroad who are outstanding experts and scholars in their fields. This series will be of interest to researchers, lecturers, and graduate students alike.

Advanced Topics in Science and Technology in China aims to present the latest and most cutting-edge theories, techniques, and methodologies in various research areas in China. It covers all disciplines in the fields of natural science and technology, including but not limited to, computer science, materials science, life sciences, engineering, environmental sciences, mathematics, and physics.

Preface

Traditional strength assessment procedure implemented in marine structural design rules is highly experience-based due to the complexity of the structure and its operational environment. With the fast development of computer technology, software and hardware, the possibility to accurately assess the marine structural strength based on the strict principles of mechanics increases. The criteria which allow the direct calculations of loading and strength are often termed as first-principle-based design criteria.

However, it is widely recognized that even the latest classification rules for marine structures are still far from the "real" first-principle-based criteria. Important evidence for this statement is that the strength is assessed at different global (hull girder) and local (stiffened panel and welded joints) levels and in different failure modes (yielding, buckling and fatigue). The relationship among them is not taken into consideration and the relative success of this strength assessment procedure is largely based on past experiences. Furthermore, in most of the fatigue strength assessment methods which are *S-N* curve based, the effects of initial defects and load sequence have been ignored and the damage state has not been specified. These, together with some other factors, lead to large scatter of the predicted fatigue lives. Significant improvements with regard to the fatigue strength assessment methodology for marine structures are required.

The effect of fatigue damage on ultimate strength is not considered too. Thus, for existing marine structures operated for certain period, the strength analyzed may not represent the actual strength a marine structure possessed. Risk analysis based on the current strength analysis procedure is then rather uncertain. Inspection and maintenance decisions based on the assessment may not reflect the actual "optimum".

In order to apply the damage tolerance design philosophy to design marine structures such as ships and offshore platforms in place of the safe life philosophy currently adopted, accurate prediction of fatigue crack growth under service conditions is required. Fatigue Crack Propagation (FCP) theory could fulfil that purpose. Now, more and more people have realized that only a Fatigue Life Prediction (FLP) method based on FCP theory has the potential to explain various fatigue phenomena observed. In this book, the issues leading towards the development of a Unified Fatigue Life Prediction (UFLP) method based on FCP theory are addressed. Based on the philosophy of the unified approach, the current inconsistency between fatigue design and inspection of marine structures could be resolved.

The book is divided into eight chapters. Chapter 1 is an introduction, in which the brief history of fatigue study is summarized and the general layout of the book is described. Since most marine structures are made of metals, in Chapter 2 the latest understanding of fatigue mechanisms of metals is summarized. Chapter 3 introduces the current state-of-the-art of UFLP and the meaning of the unified approach used in this book is explained. In Chapter 4, the basic elements of fracture mechanics are introduced which is the important foundation for understanding the later chapters. Chapter 5 presents the general procedure for a UFLP method for marine structures. Chapter 6 discusses various issues related to fatigue loading, which is the main cause of fatigue failure of marine structures. In Chapter 7, some applications and demonstrations of UFLP are given, which would be helpful in the understanding of the philosophy presented in the book and further recognize the problems to be solved for engineering applications. Chapter 8 discusses the relevant issues related to the code development based on UFLP for marine structures.

This book presents the state-of-the-art and recent advances, including those by the authors, in fatigue studies. It is designed to lead the future direction and to provide a useful tool in many practical applications.

The methodologies and information in this book are addressed to engineers, naval architects, research staff, professionals and graduates engaged in fatigue prevention design and survey of marine structures, in fatigue studies of materials and structures, in experimental laboratory research, in planning the repair and maintenance of affected structures, and in rule development including in-service reliability systems, etc. The book is also an effective educational aid in naval architecture, marine, civil and mechanical engineering.

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Contents

1 Introduction

1.1 Fatigue Problems in Marine Structures

Marine structures such as ships and offshore platforms are subjected to complex loading histories and one of the most significant failure modes is fatigue (ISSC, 2009). Fatigue is defined as a process of cycle by cycle accumulation of damage in a material undergoing fluctuating stresses and strains (Almar-Naess, 1985). A significant feature of fatigue is that the load is not large enough to cause immediate failure. Instead, failure occurs after a certain number of load fluctuations have been experienced, *i.e.* after the accumulated damage has reached a critical level. The propagation of fatigue cracks may eventually compromise the structural integrity and water-tightness of marine structures, so fatigue prevention has been paid great attention by all the stakeholders of marine structures.

Historically, ship structures have been designed to meet minimum scantling requirements that have included allowances for general corrosion and uncertainties in design methods (Glen, *et al.*, 2000). Until the 1970s, fatigue cracking was not explicitly considered by designers because fatigue cracking was rarely detected in ships less than 10 years old and because the frequency and costs of repairing fatigue cracks in older ships was acceptable to owners. Since the late 1970s, however, fatigue cracking has occurred more frequently in relatively new ships.

This change has been attributed to the design and construction of more structurally optimized ships with thinner scantlings (Glen, *et al.*, 2000). This optimization, which has been motivated by commercial demands to reduce the fabrication costs and weight of hull structures, has been achieved through the greater use of high strength steels, the use of more sophisticated design tools, and the greater exploitation of classification society rules which have permitted design stresses to increase with tensile strength up to a fraction of the tensile strength defined by the so-called material factor. Unfortunately, stress concentrations of structural details have not been adequately reduced to compensate for the higher design stresses and higher local bending stresses associated with thinner scantlings.

Furthermore, the fatigue strength of as-welded steel joints is essentially independent of tensile strength. Therefore, local cyclic stresses in structural details have been permitted to increase without a matching increase in fatigue strength of these details. In addition, corrosive environments have exacerbated this mismatch since the flexibility of a thin structure promotes the flaking of rust which accelerates the wastage process and further increases the flexibility of the thin structure (Liu and Thayamballi, 1995; Skaar, *et al.*, 1987; LR, 1992).

In response to safety concerns and escalating maintenance costs for owners, classification society rules have introduced explicit fatigue design criteria for welded structural details in steel ships (Cramer, *et al.*, 1994; LR, 1996; ABS, 1992). These criteria, which are largely based on well-established fatigue design procedures for welded joints in bridges and offshore structures (UKDE, 1984; BSI, 1980; 1993), are intended to ensure that there is a low probability of fatigue failure occurring during the design life of a ship, where failure is generally considered to be the initiation of a through-thickness crack several inches long. However, premature fatigue cracking as a result of fabrication or design errors can still occur. Furthermore, some fatigue cracking can still be expected in properly designed ships. Therefore, quantitative techniques for predicting the residual life and residual strength of cracked structural welded details are needed, to develop safe but cost-effective inspection schedules at the design stage. These techniques can also be used to optimize the scheduling of repairs for cracks found in service and to assess whether the operation of existing ships can be extended beyond their original design lives (Glen, *et al.*, 2000).

1.2 Current Practices of Fatigue Strength Assessments and Their Deficiencies

Current Fatigue Strength Assessment (FSA) methods for marine structures such as ships are all stress-based using nominal, hot-spot or notch stresses (*e.g.* CSR of IACS, 2006). A linear damage accumulation rule is used which ignores the load sequence effect and the long term distribution of the random loading is often assumed to follow the Weibull distribution (1951). The damage index at failure is always assumed to be a constant no matter what the initial state of the structure and the final state of the fatigue failure are. Due to other differences in the FSA process, such as definition of loading, choice of *S-N* curves and calculation of Stress Concentration Factors (SCFs), different FSA procedures result in large scatter of fatigue lives for the same detail. A recent comparative study on fatigue strength assessment procedures adopted by different ship classification societies indicated a large difference (from 1.8 years to 20.7 years) in the predicted fatigue life for a very simple detail (Fricke, *et al.*, 2002).

The current approach adopted by the International Association of Classification Societies (IACS) for reducing the scatter is unification (*e.g.* CSR of

IACS, 2006). It is the authors' belief that unification will not completely solve the actual problem of scatter. The Cumulative Fatigue Damage (CFD) theory itself is also subjected to some theoretical flaws and is responsible for the main scatter. This is based on the following arguments.

A fatigue life scatter of 10 times for practical structures is certainly not acceptable because a fatigue life of 3 years has a completely different interpretation to a fatigue life of 30 years in a ship. However, if we realized that this scatter of 10 times also exists in well-controlled "identical" small specimens (*e.g.* Hanaki, *et al.*, 2010), the scatter can only be attributed to the sizes of initial defects or the competing failure modes induced separately by surface- and internally-initiated cracks (Ravi Chandran, *et al.*, 2010; Cashman, 2010).

Much experimental evidence (Skorupa, 1998; 1999; Qian and Cui, 2010) has also shown that for variable amplitude loading, the load sequence effect is also very significant. It is well known that for high-low loading, the damage index is less than 1 due to the underload acceleration while for low-high loading, the damage index is greater than 1 due to the overload retardation.

The total error between prediction and experiment can be written as Eq. (1.1) where each term represents an individual factor. From the above arguments, we can say that the scatter induced by initial defects and the load sequence is of the same order as that induced by differences in definition of loading, calculation of SCFs and choice of *S-N* curves. Thus, attention only paid to the calculation accuracy of SCFs and choice of *S-N* curves will not be able to reduce the total scatter significantly. Therefore, currently-used stress-based approaches for FLP of ship structures are subjected to theoretical flaws.

$$\varepsilon_{\text{tot}} = \sqrt{\varepsilon_{\text{SCF}}^2 + \varepsilon_{S\text{-}N}^2 + \underbrace{\varepsilon_{\text{sequence}}^2 + \varepsilon_{\text{initial crack}}^2 + \varepsilon_{\text{final crack}}^2 + \cdots}_{\text{ignored by CFD theory}}} \tag{1.1}$$

Now, more and more people have realized that only an FLP method based on FCP theory has the potential to satisfy the accuracy requirement and to explain various fatigue phenomena observed. This is the fundamental philosophy for the development of a UFLP method for marine structures.

1.3 Historical Overview of Metal Fatigue

Marine structures are mostly made of metals, so a historical overview of metal fatigue would be helpful in understanding the UFLP method. According to Schütz (1996), the history of fatigue begins with Albert. In 1837, he published the first known fatigue-test results. In 1842, Rankine discussed the fatigue strength of railway axles. The term "fatigue" was mentioned for the first time by the Englishman Braithwaite in 1854. In his paper, Braithwaite described many service fatigue failures of brewery equipment, water pumps, propeller shafts, crankshafts, railway axles, levers, cranes, *etc*. Beginning in 1860, Wöhler published the results of fatigue tests with railway axles. In 1870, he presented a final report containing the following conclusions, often called "Wöhler's laws": "Material can be induced to fail by many repetitions of stresses, all of which are lower than the static strength. The stress amplitudes are decisive for the destruction of the cohesion of the material. The maximum stress is of influence in so far as the higher it is, the lower are the stress amplitudes which lead to failure. Wöhler therefore stated the stress amplitude to be the most important parameter for fatigue life, but a tensile mean stress also has a detrimental influence".

Wöhler incidentally represented his test results in the form of tables. Not until 1910 did Basquin (1910) represent the finite life region in the form " $\log \sigma_a$ on the ordinate, log*N* on the abscissa" and these curves were called "Wöhler's curves" since 1936 and now they are called *S-N* curves.

The next progress was the discovery of the Bauschinger effect in the period 1870–1905, "the change of the elastic limit by often repeated stress cycles", which is the basis for the hypotheses of Coffin and Manson which originated in the 1950s and which are still being utilized today in the Low Cycle Fatigue (LCF) field and for FLP according to the local concept.

In the period 1920–1945, the foundations were laid for almost all the fatigue knowledge we enjoy today. These include the fatigue strength under variable amplitudes, the measurement of fatigue loads and load spectra, the realization that higher-strength materials do not result in higher fatigue strengths of components, the mechanical methods to improve fatigue strength by inducing compressive residual stresses, the damage accumulation hypotheses of Palmgren-Miner for FLP under variable amplitudes, the statistical scatter of the static and fatigue strengths of materials, the realization that it is difficult, if not impossible, to transfer the fatigue behavior of specimens to that of an actual component, which is true even today.

The period 1945–1960 when the knowledge gained in the years 1920–1945 was utilized. In all industrial countries fatigue was investigated. Due to the well known crashes of the Comet airliner, many full-scale fatigue tests were carried out on fuselages. In this period, the "safe life" concept was gradually replaced by the "fail safe" concept. The scatter of the number of cycles to failure and of the fatigue limit was treated with the help of mathematical statistics.

From about 1950 onwards, doubts about the validity of Miner's rule began to appear in the literature. Damage sums between 0.1 and 10 were found in fatigue tests which, however, were entirely unsuitable for this purpose. A genuine check of Miner's rule was only possible at the end of the 1950s, as only then had suitable test machines been developed.

Toward the end of the period 1945–1960, a large number of crack propagation tests were carried out and crack propagation hypotheses were developed, still without employing Fracture Mechanics (FM). However, in 1958, Irwin had realized that the stress-intensity factor $K = \sigma\sqrt{\pi a}$ was the determining factor for static strength in the cracked state. With this concept, Linear Elastic Fracture

Mechanics (LEFM) was born.

From 1960 onwards, the most significant progress in fatigue was made by applying LEFM. Various FCP theories were proposed although CFD theories were further developed and widely applied in most industries except the aircraft industry (Fatemi and Yang, 1998; Yang and Fatemi, 1998; Cui, 2002; 2008).

Paris, *et al*. (1961; 1963) established that FCP could be described by the following equation, soon erroneously called a "law",

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\left(\Delta K\right)^{n} \tag{1.2}$$

This equation was widely accepted and is used even today. However, it contains neither the influence of mean stress on crack propagation, nor the final fracture on reaching the unstable fracture condition, $K_{\max}=K_{\mathrm{Cf}}$, nor the fatigue threshold ΔK_{th}, which is the SIF range below which no FCP occurs. The complex process of crack propagation is undoubtedly described much too simply by this equation.

In order to explain the stress ratio effect $R(=K_{\min}/K_{\max})$, Elber (1970) introduced the "crack closure" concept based on his experimental observation that after a high tensile load the crack closes before the load is reduced to zero.

This concept had been highly appraised in the 1980s and 1990s and it was used to explain various other effects including the load sequence effect (*e.g.* McEvily, *et al*., 1999; McEvily and Ishihara, 2001; Newman Jr., *et al*., 2006) but now it is subjected to some challenges (*e.g.* Hertzberg, *et al*., 1988). In particular, many people have agreed that the physical effects of crack closure have been greatly over-estimated in the past (*e.g.* Vasudevan, *et al*., 1994). The partial crack closure model (Donald and Paris, 1999; Kujawski, 2001a; 2001b) was proposed to overcome the difficulty the crack closure model met. Later, Kujawski (2001c; 2001d) further found that without using the crack closure concept, it is possible to explain the stress ratio effect, even better than by using the concept. Vasudevan, Sadananda and their co-workers (*e.g.* Vasudevan, *et al*., 2001) had proposed the two-parameter unified approach. According to the unified approach it is both $K_{\max}$ ($\sigma_{\max}$) and ΔK ($\Delta\sigma$) which are responsible for the FCP. Through their efforts the unified approach has demonstrated that all the recognized special phenomena can be explained. Now, more and more people tend to believe that this unified approach might be a correct way forward (Noroozi, *et al*., 2005; Stoychev and Kujawski, 2005; Kujawski, 2005; Zhang, *et al*., 2005; Maymon, 2005a; 2005b).

The load sequence effect might be the most challenging problem for the FLP of engineering structures. Although the problem has been studied since the 1960s, the mechanism which causes the load sequence effect has not been understood yet (Skorupa, 1998; 1999). Generally speaking, three classes of mechanisms acting before, at or after the crack tip have been proposed in the literature. De Castro, *et al*. (2005) have discussed extensively the three classes of mechanisms and they found that "plasticity induced crack closure (behind the crack tip) cannot explain