

## FRACTURE RESISTANCE OF SHIP LONGITUDINAL MEMBERS INCLUDING FATIGUE CRACK

Yann Quéméner\*

Chien-Hua Huang

Chi-Fang Lee

Research department  
China Corporation Register of Shipping  
Taipei, Taiwan (ROC)

### ABSTRACT

This study investigates the fracture failure of longitudinal members including cracks. Specifically, this study employs the failure assessment diagram methodology to assess the conditions of failure at the crack tip. Based on various crack configurations, this study establishes the analytical formulations of the crack-tip condition that are validated using finite element analyses. In addition, the material toughness is expressed in terms of crack-tip opening displacement. This study evaluates the failure stress of representative cracked members as a function of the crack length. This enables determining critical crack lengths corresponding to the maximum stresses derived from extreme loads. Finally, this study uses simplified fatigue crack growth analyses to characterize the critical crack length in terms of fatigue life. For members located in the deck and bottom regions, the critical crack lengths correspond to the end of the assessed fatigue life. Therefore, the fracture resistance of the longitudinal members is satisfactory as it will not cause the premature loss of the component. This study also provides analytical formulations for crack-tip conditions that could be employed in a reliability study linking fatigue crack growth and fracture under extreme loads.

Keywords: Fracture, Longitudinal member, FAD, CTOD

### 1. INTRODUCTION

During the ship's lifetime, fatigue cracks may initiate in the ship's structure. These cracks can propagate to a length that can be critical in view of the fracture when the ship encounters extreme loading conditions. This critical crack length characterizes the fracture resistance of the structural members.

It is well accepted that ship design and fabrication provides sufficient fracture resistance to the structure. IACS [1] states

that, in ships, inherent redundancy prevents the local loss of a structural member from immediately endangering the global structural integrity. Steel toughness is also finely controlled to ensure that fatigue cracks do not result in extensive brittle fractures, as it has occurred in the past for the Liberty ships.

However, the newly adopted goal based ship construction standards (GBS) [2] provide that the actual redundancy in ship design must be demonstrated. Researchers have proposed various approaches to address this problem. Guedes Soares et al. [3] analyzed the effects of fatigue crack growth on the ship global strength, yet neglected the fracture as the governing mode of component loss. Dinovitzer et al. [4] analyzed the fracture toughness of typical longitudinal members in the ship structure using the failure assessment diagram (FAD) methodology of the British Standard [5]. The European fitness-for-service network (FITNET) [6] developed also a structural integrity assessment procedure (SINTAP) to determine the significance of cracks in terms of fracture. Within SINTAP project, Wallin et al. [7] proposed a material fracture toughness estimation scheme.

Thus, this study presents a quantitative evaluation of fracture resistance of typical longitudinal members including fatigue cracks. This fracture resistance is then compared to the fatigue life of the cracked member.

This article consists of three sections. The first section presents the conditions of failure by fracture and its evaluation using the FAD methodology. The second section evaluates the fracture resistance of typical longitudinal members including various crack configurations. Finally, the third section presents simplified fatigue crack growth analyses, allowing the characterization of the fracture resistance in terms of fatigue life.

## 2. FRACTURE FAILURE

### 2.1 Fracture mechanics

The fracture mechanics field of interest is the analysis of the mechanisms of the crack propagation in materials. Usually, two categories are identified: the linear-elastic fracture mechanics (LEFM) and the elastic-plastic fracture mechanics (EPFM). The LEFM theory, which is governed by brittle fracture, is reasonably well established, and the stress intensity factor (SIF or  $K$ ) approach is the most widely employed (e.g.: fatigue assessment). However, the steel employed in ship construction is carefully controlled to ensure that fractures occur in a ductile manner. The ductile fracture cannot be assessed accurately by methods purely based on LEFM theory. Thus, some situations require the use of the EPFM using approaches such as the crack-tip opening displacement (CTOD).

The applicability of each field of fracture mechanics is not clearly defined. Thus, the failure assessment diagram (FAD) methodology is a very practical approach because it encompasses the full range of fracture behaviour.

### 2.2 Failure Assessment Diagram

This study is based on the FAD methodology proposed by the British Standard [5]. A sounder theoretical background of this approach can be found in [8]. The British Standard proposes three levels of fracture assessment. The choice of the level depends on the amount of input data available and the desired degree of precision of the results. This study uses the “Level 2”, defined as the “normal assessment”.

The failure assessment diagram principle is based on the interaction between fracture and collapse in a structural component including a crack. Figure 1 presents the failure assessment diagram corresponding to the Level 2.

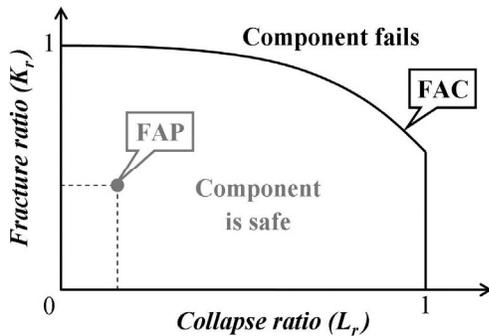


Figure 1. Failure assessment diagram

In the ordinate, the fracture ratio ( $K_r$ ) is the ratio of the applied crack driving force to the fracture toughness of the material. In the abscissa, the collapse ratio ( $L_r$ ) is the ratio of the applied load to the limit load of the structural member.

The failure assessment curve (FAC) represents the predicted limit conditions of the modes of failure, from a brittle to a ductile fracture. Equation (1) provides the Level-2's FAC expression for  $L_r$  from zero till unity. If  $L_r$  is greater than unity,

$K_r$  is simply set to zero, because this study does not consider the failure by collapse that occurs beyond  $L_r=1$ .

$$K_r = (1 - 0.14L_r^2) \cdot [0.3 + 0.7 \exp(-0.65L_r^6)] \quad (1)$$

A failure assessment point (FAP) can be determined for a given loaded cracked component. If the FAP is included in the area below the FAC (see Fig. 1), the considered component is not supposed to fail. An FAP above the FAC represents an unacceptable level of crack which may cause the component failure. In addition, an FAP close to the vertical axis means that the potential fracture is brittle. However, an FAP in the vicinity of a collapse ratio equal to unity indicates that the potential failure is characterized by the global yielding of the considered structural member.

The fracture ratio expression (see Eq. (2)) is a ratio of the crack driving force represented by the Mode I stress intensity factor ( $K_I$ ) to the material toughness  $K_{mat}$ , which is derived from the measured CTOD ( $\delta_{mat}$ ).

$$K_r = \frac{K_I}{K_{mat}} = \sqrt{\frac{K_I^2}{X \cdot \sigma_Y \cdot \delta_{mat} \cdot E'}} \quad (2)$$

where  $\sigma_Y$  is the material yield stress and  $E'$  is the elastic modulus corrected for constraint conditions ( $E'=E$  for plane stress,  $E'=E/(1 - \nu^2)$  for plane strain). The term  $X$  is set to 1 as proposed by the British Standard [5] for the case in which  $X$  is not quantified by structural analyses. Equation (3) defines the stress intensity factor ( $K_I$ ).

$$K_I = \sigma \cdot Y \sqrt{\pi a} \quad (3)$$

where  $\sigma$  is the applied stress,  $Y$  is a dimensionless function related to the crack configuration, and  $a$  is the crack length.

Equation (4) provides the collapse ratio expression.

$$L_r = \frac{P}{P_0} \quad (4)$$

where  $P$  is the applied load and  $P_0$  is the limit load at which the cracked structural member's yield strength is reached.

The FAD approach classifies stresses based on their nature. The primary stresses  $\sigma_p$  are defined as the loads applied to the structure, whereas other stresses, including the residual stress, coming from the fabrication process, are categorized as secondary stresses  $\sigma_s$ . A significant property of secondary stresses is that they cannot by themselves cause plastic collapse because they arise from stress/displacement limited phenomena. However, they contribute to the severity of the local condition at the crack tip. Their contribution adds to the primary stress in the  $K_I$  expression (see Eq. (3)) by replacing  $\sigma$  with  $\sigma_p + \sigma_s$ .

Finally, if the structure is loaded with a combination of primary and secondary stresses, the resulting plasticity effects cannot be evaluated by a simple linear addition of the effects resulting from the two independent stress systems. The FAD includes a term  $\rho$  in the definition of the fracture ratio to cover the