Adopting a Risk-based Design Methodology for Flooding Survivability and Structural Integrity in Collision/Grounding Accidents

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ABSTRACT

Traditionally, when the watertightness of a ship is compromised emphasis is placed on the assessment of survivability under the explicit assumption of structural integrity. However, such assumption could be inappropriate in case where progressive degradation of the structure seriously impedes the potential of the ship to recover from a serious damage. To tackle this problem, a risk-based design methodology is adopted which addresses the coupled problem of loss of survivability due to progressive flooding and loss of structural integrity due to progressive structural failure of a damaged ship. Considering the maturity of the first part of the methodology, this paper reports on the progress achieved in the latter part and paves the way for further development in the near future.

KEYWORDS

Progressive Structural Failure; Progressive Flooding; Crack Propagation

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Seungmin Kwon has graduated with MSc. (2000) from the Department of Naval Architecture and Ocean Engineering, Seoul National University, Republic of Korea and worked for Daewoo Shipbuilding and Marine Engineering (DSME). Currently he is conducting a PhD course with support of DSME in the Ship Stability Research Centre (SSRC), Department of Naval Architecture and Marine Engineering, University of Strathclyde. His study is focusing on implementation of Risk-based Ship Design taking into account coupled problem of progressive flooding and progressive structural degradation in a damaged ship.

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Dracos Vassalos is Professor of Maritime Safety in the Department of Naval Architecture and Marine Engineering of the University of Strathclyde and the Director of the Ship Stability Research Centre (SSRC), a world-leading centre of excellence on ship stability and safety. His motto is "safety enhancement through innovation", an idea he has pursued single-mindedly in a career that spans over 30 years in industry and academia, promoting the use of scientific approaches in dealing with maritime safety. He has been instrumental in helping to create a critical mass in the research community on safety, through a series of initiatives that made SSRC the focus of active international collaboration. He travels the world over promoting maritime safety, lectures and publishes widely, with some 400 technical publications, 4 patents and 7 books/Conference proceedings to his credit and a string of prizes and awards, including some 100+ major research contracts amounting to over £20M. He served as Head of Department (1997-2007), Chair of the STAB Conferences and Workshops (1996-2006), Chair of the ITTC Stability Committee in Waves (1996-2002), Chair of WEGEMT (the European Association of Universities in Marine Technology 1999-2001).

Currently, Professor Vassalos is Chairman of the International Standing Committee of the "Design for Safety" Conference, a theme instigated and promulgated by SSRC. He is also a long-standing member of the UK delegation to IMO for ship stability and safety.

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George Mermiris has graduated with MEng (2003) and PhD (2010) from the Department of Naval Architecture and Marine Engineering, University of Strathclyde. Currently he is a Research Fellow in the Ship Stability Research Centre (SSRC). The core of his work is on Risk-based Design methodology and implementation with main emphasis on structural analysis and collision dynamics, advanced mathematical modelling and risk analysis. He has authored 10 journal and conference papers in this area.

INTRODUCTION

Loss of watertightness of a ship (due to accidental loading or structural failure) leads to a series of changes in her dynamic behaviour in a seaway. The ensuing sinking/heeling and potential loss of stability in the damaged condition as a result of progressive flooding has been covered extensively and to great depth in the literature, e.g. (Vassalos et al., 2005), for passenger ships.

On the other hand, an issue that has has received only approximate treatment to date is the progressive structural degradation of the hull girder of the damaged ship. The presumption of structural stability for the survivability assessment of passenger ships is primarily attributed to the fact that (i) they are inherently robust, and (ii) if capsize is going to take place, then this will most probably happen within the first half-hour following the side shell breach, (Vassalos, 2007), i.e. a very short interval for any substantial loss of structural integrity.

However, the newly introduced framework of the Safe Return to Port has set one more dimension to this problem. That is, under the premise that *the ship should be designed to be her own best life boat*, it was recommended that a ship should remain afloat, upright and habitable for 5 days until it can return to port under her own power or until assistance arrived, (IMO, 2004). Depending on the extent of the initial damage and the prevailing weather conditions, this time period is sufficient for total structural failure to occur.

Moreover, other safety-critical ships, like tankers, are much more prone to such progressive structural failure, with large potential for serious environmental impact. *Prestige* is among the most recent accidents that signify the importance of a methodology for the quantification of the residual strength of the hull girder. In these particular cases, knowledge of the timeline and pattern of the damage propagation would be invaluable in the course of establishing the appropriate mitigation actions and more importantly in designing for adequate structural integrity.

In response to this requirement, this paper reports on recent developments of a first-principles methodology for the simulation of progressive structural failure in case of collision/grounding damage and its interaction with the flooding mechanism in the time domain. Considering that the study of flooding has matured over the past 30 years, the focus, for the time being, is placed on the damage evolution and the evaluation of the ultimate residual strength of the damaged ship. To demonstrate the proposed methodology a girder box is considered in various damage cases with encouraging results.

PROGRESSIVE STRUCTURAL FAILURE

The complicated nature of progressive structural failure requires deployment of FE analysis. In this work, this will be performed using ABAQUS.

The fracture evolution is addressed as crack propagation using 'Paris Law', in which 'time' is included indirectly in number of cycles, *N*, where '*N=time/period*' in equation (1).

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

Where, $\frac{da}{dN}$ is crack propagation rate with units of [metres/cycle]; ΔK is range of Stress Intensity Factor (SIF), K_{max} - K_{min}, with units of [MPa$\sqrt{m}$]; C and m is material constant for crack propagation.

The fracture behaviour in ABAQUS is modelled with the Virtual Crack Closure Technique (VCCT) for the calculation of the strain energy release rate (G), and, in turn, the calculation of the SIF (K) as shown in equation (2) next.

$$G = \begin{cases} \frac{K^2}{E} & \text{for Plane Stress} \\ \frac{K^2}{E}(1-\nu^2) & \text{for Plane Strain} \end{cases} \qquad (2)$$

Where, E is Young's modulus and ν is Poisson's ratio. Hence a procedure for evaluating progressive structural failure using 'Paris Law' and VCCT can be formulated as depicted in Fig. 1.

According to Leski, (2007), VCCT is based on Linear Elastic Fracture Mechanics (LEFM), which can be used under conditions of little or negligible plastic deformation around the crack tip. Therefore, it is justifiable to use VCCT in this research as long as the crack propagation is considered under yield strength limits.

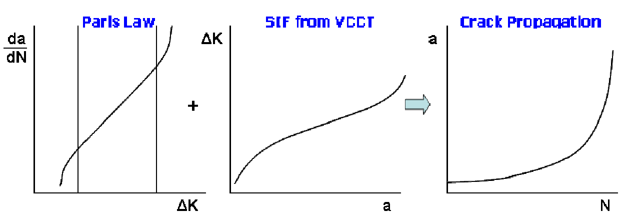


Fig. 1: Proposed procedure of progressive structural failure

Sensitivity Analyses

Sensitivity analysis is carried out to investigate the applicability of VCCT for calculating SIF. The following subsections elaborate on these results.

<u>Effect of an opening (hole)</u>

Because damage can be attributed to collision/grounding accidents, cracks emanating from an opening are important. Substantial investigation has been carried out on cracks from rivet holes in aircraft structures. The single and double cracks at the circular hole-edge have been studied by Bowie (1956), Newman (1971), Tweed et al. (1973) on infinite and finite plates.

Validation of VCCT for taking into account the effect of a hole is performed by comparing its results with those from Newman (1991). Fig. 2 shows the normalised SIF values from VCCT in a finite plate with a hole of radius R. It can be seen that VCCT captures the effect of a hole in a satisfactory manner.

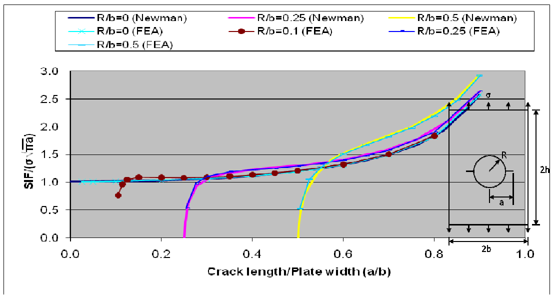


Fig. 2: SIF ratio in a finite plate with a hole, compared with Newman, (1971)

<u>Stress Distribution</u>

Basic analytical solutions assume that the stress on the edges of cracked plate is uniformly distributed. In reality however, normal stresses vary linearly due to distribution of bending moment. To investigate the effect of this, a load model is tested and results are compared with empirical solution results from Chell (1976). The SIF results from VCCT are excellent agreement with Chell as can be seen in Fig. 3.

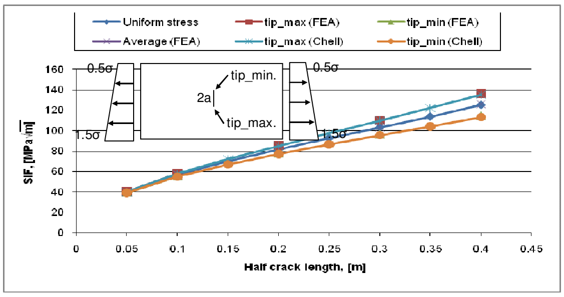


Fig. 3: SIF due to linearly varying stress distribution, compared to Chell, (1976)

Stiffener Contribution

Not so much research has been carried out on crack propagation in stiffened panels; the few references include Poe (1971) and Dexter et al. (2000)

A stiffener is considered to restrain propagation of crack in a stiffened panel because its presence in front of a crack tip serves as an increased net section of the member. Fig. 4 shows the stiffener effect based on tests conducted by Poe, (1971).

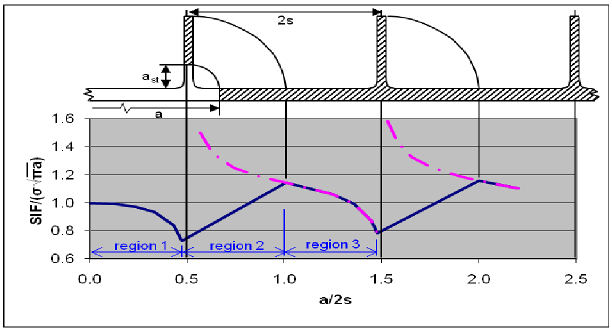


Fig. 4: Stiffener effect, reproduced from Poe (1971)

This tendency of SIF ratio in stiffened panels can be established using VCCT (Fig. 5), which shows results for different stiffener depths. Although VCCT is not in full agreement with Poe's results, it captures the effect of stiffener consistently.

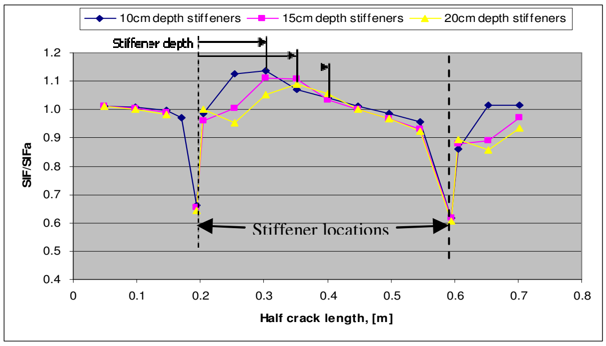


Fig. 5: SIF ratios calculated by VCCT, for different stiffener depths

Variable Load Amplitude

Normal crack propagation is based on application of constant load amplitude, which is considered conservative compared to variable load amplitude application. According to Makabe (2004), Silva (2007) and others, an overload (OL) in constant stress amplitude delays crack propagation by rendering crack closure effect more prominent, while an "underload" (UL) increases crack propagation rate. An example from Silva (2007) is shown in Fig. 6.

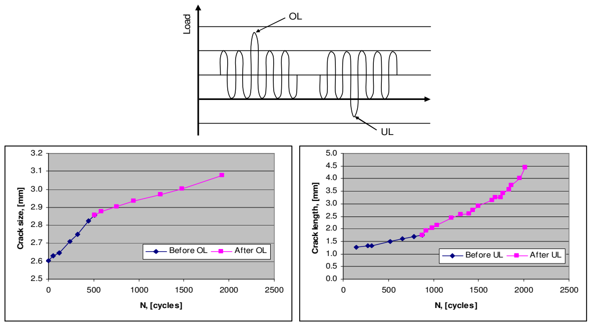


Fig. 6: Changes in crack propagation due to alteration of overloading and "underloading", reproduced from Silva (2007)

As a first step in considering the effect of variable amplitude load directly, an equivalent constant amplitude loading is used. To this end, an estimation of the equivalent stress range in various stress range loading distributions is formulated as follows based on Miner's rule;

$$\Delta\sigma_{eq} = \sqrt[m]{\sum(\Delta\sigma_i^{\ m} \times n_i) / \sum n_i} \qquad (3)$$

Where, i denotes i-th stress range; n_i is number of cycles having stress range of $\Delta\sigma_i$; m is material coefficient in 'Paris Law'.

Lateral Loading

When a ship is damaged, the water ingress and egress from the flooded compartment will induce stresses on the cracks near the damage.

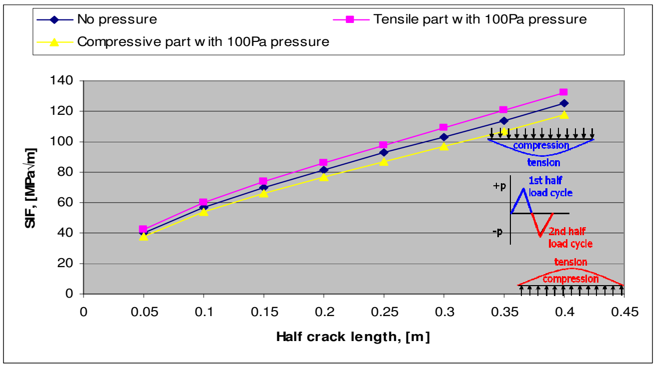


Fig. 7: The effect of lateral load on SIF

A plate subjected to lateral loading experiences alternating tension and compression on either side depending on the direction of loading. SIF is reduced on the compressed surface and increased on the surface under tension (Fig. 7).

However, considering a complete load cycle of water ingress and egress, both surfaces experience tension and compression. Hence using the same SIF on both surfaces is reasonable.

RESIDUAL STRENGTH

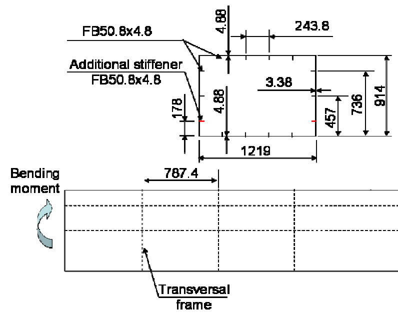
The post-damage residual strength assessment of a ship is based on a simplified moment-curvature relationship for stiffened panels, (Gordo et al., 1996).

The moment-curvature result is obtained by imposing a "curvature" from sagging to hogging on the hull girder, which is assumed to consist of several beam-column elements. For each curvature, the average strain of each element is calculated and the stress imposed on each element is obtained from the corresponding load-shortening curve. The moment sustained by the whole section is obtained by summing up the moments of each element induced by axial force and distance of each element from the neutral position of the section. The ultimate bending strength of the section is the maximum bending moment in the moment-curvature curve in hogging and sagging conditions.

The load-shortening curve of each element is obtained according to Gordo et al. (1993), who adopted an elastic-perfectly plastic behaviour of material for each element. Defining a load-shortening curve includes the effect of plate induced failure, flexural bucking failure of column and tripping failure of stiffener. The effects of residual stress and initial deformation are also considered.

APPLICATION TO A SMALL BOX GIRDER

A small barge-shaped box girder, used for ultimate strength tests by Dowling et al. (1973), is considered for estimation of the crack propagation and residual strength assessment. The box particulars are shown in Fig. 8. In order to reduce modelling complexity, flat bar stiffeners are used. Only the modulus of elasticity of material is used for compliance with LEFM.



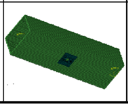
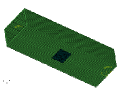
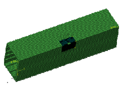
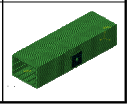
Components	E (GPa)	ν
Upper flange	208.5	0.3
Lower flange	208.5	0.3
Side	216.2	0.3
Stiffener	191.5	0.3
Trans. frame	191.5	0.3

Fig. 8: Dimensions of Dowling's box girder (all lengths in mm)

Description of Damages

Three damage cases are considered in the midship region; (a) bottom damage representing a grounding case with and without opening, (b) a bilge damage representing either a collision or grounding case, and (c) a side shell damage also representing a collision case. Detailed descriptions including initial conditions on the damage cases are summarised in Table 1.

Table 1: Descriptions of damages considered

Damage cases	Bottom damage		Bilge damage	Side damage
R, [mm]	65	No hole	65	65
a_0, [mm]	10.9	75.9	10.9	10.9
ΔBM, [MN-m]	0.7	0.7	0.7	1.2
FE model				

SIF Calculation

SIF was calculated using VCCT at crack tip for each damage case using unit bending moment of 10 KN-m. Symmetric crack propagation is assumed for the bottom damage case while asymmetric crack propagation is applied to bilge and side shell damage cases (Fig. 9).

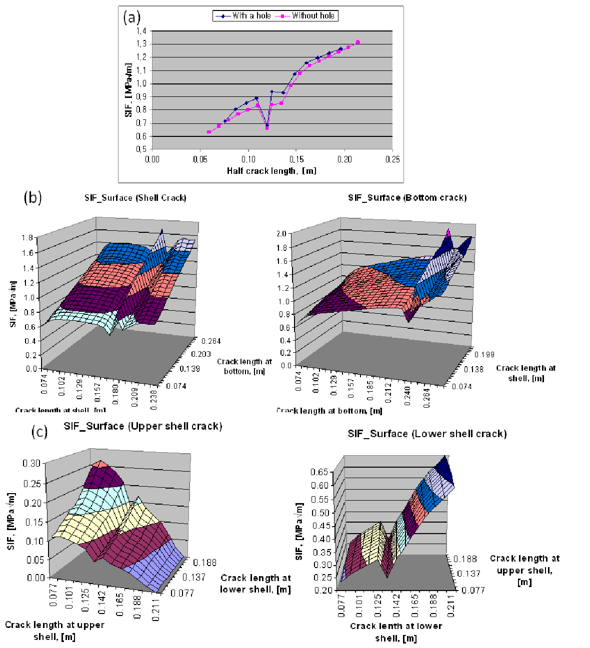


Fig. 9: SIF curve for bottom damage (a); SIF surfaces for bilge damage (b) and side damage (c)

Progressive Structural Failure Analysis

Crack propagation analysis is carried out according to Paris Law with the calculated SIFs. The material constants of *C* and *m* are selected as 9.5e-12 and 3.0 respectively according to BS PD 6493 (1993). The estimated crack size of each damage case is shown in **Error! Reference source not found.**. The time scale in the horizontal axis is obtained by assuming a wave period of 6 sec, typical of the modal period of an undeveloped sea.

The results obtained show that the bottom damage is the fastest crack propagation case while the side damage case shows the slowest.

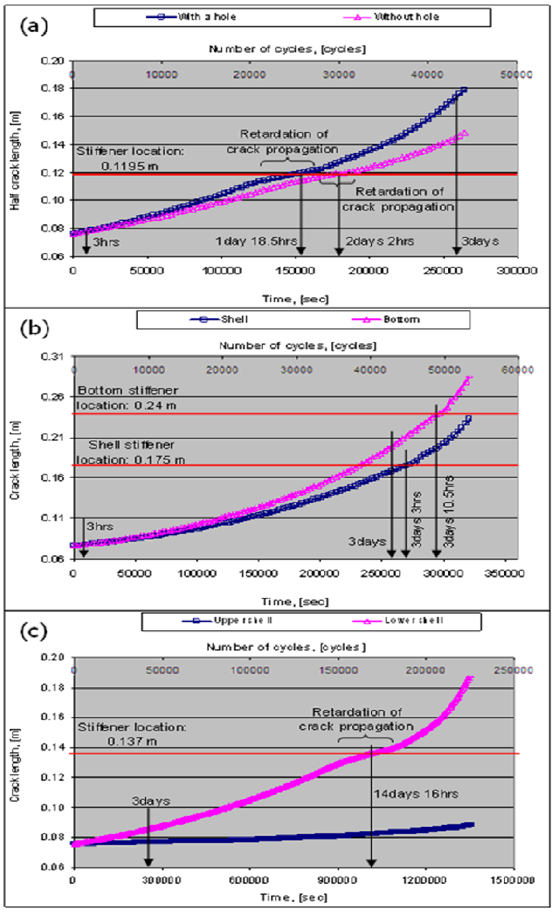


Fig. 10: Crack propagation analysis results for bottom (a), bilge (b) and side shell (c) damage cases

Residual Strength Analysis

Residual strength analysis is carried out and the results for initial damage and final damage cases are shown in Fig. 11. It should be noted that all the initial damage cases are assumed not to include any stiffener damage. Also no heel due to possible flooding is considered.

It is found from the results, Table 2, that all damage cases resulted in reduction of ultimate bending strength in both hogging and sagging conditions, except side damage in sagging condition. Reduction in ultimate hogging bending strength for bottom and bilge damage cases is significant.

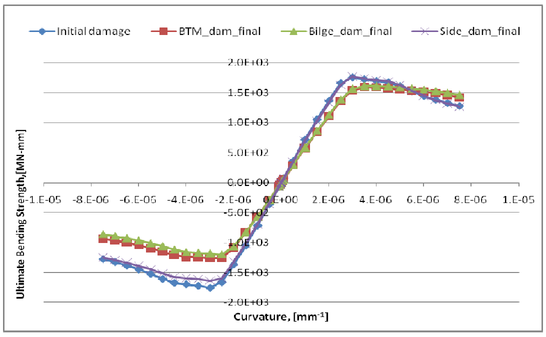


Fig. 11: Ultimate residual strength analysis results; negative curvature denotes hogging

Table 2: Ultimate residual bending strength, [GN-mm]

	Initial damage	BTM final		Bilge final		Side final	
Hog	1.75	1.26	-28%	1.20	-31%	1.64	-6%
Sag	1.75	1.60	-9%	1.61	-8%	1.77	+1%

CONCLUSIONS

On the basis of the results obtained in the simple case considered in this paper, the following conclusions can be drawn:

- A methodology comprising 'Paris Law' and VCCT is promising for the problem at hand.
- From sensitivity analysis results, VCCT in ABAQUS is proved to calculate SIF easily and accurately including important parameters.
- Ultimate strength analysis is used for the estimation of the residual strength of the damaged ship as the deterioration of structure progresses.
- Results of application to Dowling's box girder show that the proposed methodology is appropriate not only for evaluating progressive structural failure but also for estimating the residual strength of the damaged section.

FUTURE WORK

The results presented here reflect only part of the proposed methodology for the assessment of the residual strength of a ship following damage initiation either by accidental loading or own structural degradation. The next steps are (i) the application of the method to a ship-like structure and investigation of its applicability and limitations, (ii) the integration with flooding simulations, and (iii) the derivation of knowledge-intensive models that will be available in a design and operational context.

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