Ocean Engineering 106 (2015) 115–127

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Investigation into the dynamic collapse behaviour of a bulk carrier under extreme wave loads

Weijun Xu *, Wenyang Duan, Duanfeng Han

College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China

ARTICLE INFO

Article history:
Received 11 December 2014
Accepted 6 July 2015
Available online 24 July 2015

Keywords:
Dynamic collapse behaviour
Hydro-elastoplasticity approach
Severity of collapse
Extreme waves
Exceedance probability
Bulk carrier

ABSTRACT

The aim of this paper is to quantitatively evaluate the extent of collapse of a bulk carrier when the ship is subjected to extreme wave loads. A hydro-elastoplasticity theory, which was proposed by the present authors and takes into account the interaction between the large elasto-plastic deformation and the wave load evaluation, is applied to the ship's structure with the assumption that a plastic hinge is formed in the midship region when the hull girder collapses in extreme wave conditions. The dynamic response of the hinge can be expressed by the relationship between the vertical bending moment and the curvature, which are obtained using nonlinear Finite Element Analysis (FEA). A comparative correct moment–curvature curve and a reasonable load evaluation are necessary for prediction of the severity of the collapse for the actual ship. A bulk carrier hull model with one frame space is constructed and analysed using an arc-length control method (Riks method). The geometric nonlinearity resulting from large deformations and the material nonlinearity are taken into account. The presence of an initial imperfection is considered using the consistent imperfection mode method in the FEA. A prediction of the extent of collapse for a bulk carrier subjected to an extreme wave load is carried out using the hydro-elastoplasticity approach. This analysis clarifies the extent to which the hull girder may collapse in extreme wave conditions at an exceedance probability of 1/1000 in several short-term sea states.

1. Introduction

The capacity of a ship's hull girder to withstand a longitudinal bending moment must be addressed to assess the hull girder's ultimate strength, and many researchers have devoted efforts to the study of the hull girder capacity. An evaluation of the post-ultimate strength behaviour can be estimated using a hierarchy of methods, including (a) simple "closed-form" formulations initially proposed by Caldwell (1965), (b) Smith methods based on Navier's hypothesis and the average stress–average strain relationship for individual panels proposed by Smith (1977), (c) full nonlinear FEA first attempted by Chen et al. (1983) following attempts by Kut et al. (1985) and Valsgård et al. (1991), and (d) simplified FE methods such as the Idealized Structural Unit Method (ISUM), which were initially proposed by Ueda and Rashed (1984) to perform progressive collapse analysis on the transverse frame of a ship structure.

In recent years, significant efforts have been devoted to methods (a), (b) and (d). Mansour and Thayamballi (1980) applied the simple "closed-form" formulations to analyse the limiting condition when the ship's hull girder failed to perform its function, and the ultimate strength of the hull girder was determined. In this research, the buckling and instability of the hull-stiffened plates, the fully plastic yield moments, and the shakedown moments were developed. Yao and Nikolov (1991, 1992) proposed a simple and practical analytical method to simulate the progressive collapse behaviour of ship's hull subjected to longitudinal bending based on Smith's method for estimating the load-carrying capacity of a ship's hull, including the post-ultimate strength behaviour. More recent developments may be found in Yao et al. (2006). The ISUM rectangular plate and stiffened panel elements were developed by Ueda et al. (1995) and were implemented in ALPS/ISUM by Paik et al. (1996) based on the effective width concept. A new concept of the ISUM plate element that introduced the shape functions for deflection was proposed by Masaoka et al. (1998) and was further extended to the ISUM stiffened panel model by Fujikubo and Kaeding (2002). New ISUM elements have been developed by Fujikubo et al. (2002) to analyse the collapse behaviour for the double bottom structure in ships under combined thrusts and lateral pressure. The fundamental collapse modes and localised failures in the double bottom structure can be predicted with these elements, and the newest versions of the ISUM stiffened panel models have been successfully applied by Pei and Fujikubo (2005) to the analysis of progressive collapse of hull girder cross-sections.

However, fewer studies are reported regarding the use of method (c), perhaps because the approach requires significant computational and time resources. The rapid development of computer technology has enabled the use of nonlinear finite

* Corresponding author. Tel.: +86 451 8251 9902; fax: +86 451 8251 8443.
E-mail address: xuweijun@hrbeu.edu.cn (W. Xu).

http://dx.doi.org/10.1016/j.oceaneng.2015.07.006
0029-8018/

element analysis to obtain accurate results within reasonable computation times together with proper modelling of the ship's hull. Amlashi and Moan (2008) carried out the calculation in terms of the $(1/2+1+1/2)$ hold tanks of the Capesize Bulk Carrier under double bottom bending using method (c). Shu and Moan (2009) extended the model to three cargo holds and four transverse bulkheads in the midship region to investigate the ultimate strength of the Capesize Bulk Carrier. The effect of the local lateral pressure loads was considered under hogging and alternate hold loading conditions, and the calculation results were compared with those from simplified methods.

The evaluation of the ultimate strength of a hull girder is of undoubted importance for the safety of the ship, but from the viewpoint of risk-based design, the severity of hull girder collapse under wave conditions is also important because it is directly related to the consequence of the collapse. The risks may include the loss of the ship itself, the loss of cargo and lives, the occurrence of oil pollution, etc. Iijima and Fujikubo (2010) studied the target safety level of a ship's hull girder based on risk optimisation, and the conclusion showed that the target safety level is affected by the scope of the risk model. Therefore, studies should focus on the extent of the failure with the increase of interest in risk-based design. The progressive collapse behaviour of a ship's hull girder is commonly analysed in a quasi-static manner over a cross-section via displacement control, i.e., with monotonously increasing curvature. However, as Lehmann (2006) noted, the imposed forced displacement/rotation does not represent an actual loading condition, and the distributed pressure on a hull girder is the real load that acts on a ship. He stated that when the moment exceeds the maximum sustainable value, the calculation based on the input of curvature and the program that calculates the associated moment are not realistic, and in general, there is a dynamic snap-through effect to the next static equilibrium condition, a phenomena that indicates that the collapse behaviour of ship's hull girder is so complicated that it is not decided by pathways or curvatures but by forces or moments. Instead, the behaviour can be followed only if the interaction between the collapsing structure and the loads is considered, as in Yao et al. (2009). The collapse analysis was performed under load control in Phase 1. However, the post-ultimate strength could not be completely solved because the load–deformation interaction has not yet been fully considered in the studies.

Hydro-elastoplasticity is a research field in which the interaction between the fluid and the structure is considered in a range that includes the plastic deformation as well as the elastic deformation, as proposed by Kimura et al. (2010) and Xu et al. (2011a) for predicting the dynamic collapse behaviour of a hull girder in wave conditions. Iijima et al. (2011) detailed this approach and clarified the post-ultimate strength behaviour characteristics in wave conditions using numerical and tank test results. The important parameters related to the severity of the hull girder collapse were specified from the parametric dependencies study on the post-ultimate strength behaviour of a box-type hull girder in wave conditions carried out by Xu et al. (2011b, 2012). However, the hydro-elastoplasticity approach and the parametric dependencies study were based on the simplified box-type hull girder, and more realistic ship and environment models are expected to follow.

This paper primarily focuses on the investigation of the dynamic collapse behaviour of a bulk carrier under extreme wave loads. First, to obtain the capacity–displacement relationship of the bulk carrier, a ship's model with one frame space is constructed and analysed using a displacement control method. In the capacity–displacement relationship, the post-ultimate strength behaviour over a large displacement range and unloading path are taken into account. Next, the hydro-elastoplasticity analysis for the bulk carrier is carried out using the capacity–displacement relationship obtained from the finite element analysis (FEA). The inertial forces and moments and the hydrostatic and hydrodynamic loads after deformation are evaluated based on nonlinear strip theory. The identification of the Response Amplitude Operator (RAO) of the vertical bending moment, the vertical displacement in heave motion and the rotational angle in pitch motion are carried out to validate the rationality of the present approach. Finally, a good illustration of the important influence of the significant wave height on the extent of collapse of the bulk carrier under a certain exceedance probability is clarified.

2. Nonlinear finite element analysis

The most advanced analysis tools currently available for residual and ultimate strength assessment of thin-plated hull structures are nonlinear finite element codes. This paper investigates the post-ultimate strength behaviour of a hull girder in a bulk carrier using nonlinear FEA. The analysis is carried out using the commercial nonlinear FE computer program ABAQUS, which is able to solve the unstable collapse and post-buckling of structures; both geometric nonlinearity and material nonlinearity are taken into account in the procedure of nonlinear finite element analysis.

With the rapid development of computer power and technology, nonlinear finite element analysis for relatively complicated stiffened panel structures can be successfully performed to obtain relatively accurate results, and the computation time can be controlled to a reasonable extent with proper modelling of the cross-section of the hull girder. For simplicity and efficiency, certain approximations were adopted together with selected simplified methods, i.e., Smith's method and the ISUM method. For analysis of the progressive collapse behaviour of a hull girder under a longitudinal bending moment, the vertical curvature of the hull is assumed to occur incrementally, and the corresponding incremental element strains are calculated based on the assumption that the plane section remains plane and that the bending occurs about the instantaneous elastic neutral axis of the cross-section. The nonlinear finite element method solves the post-ultimate strength problem with no such assumption, and the interaction between the structural components for different buckling modes can be automatically considered in the simulation.

In the present study, the nonlinear finite element method is adopted for evaluation of the load-carrying capacity of the cross-section of a Bulk Carrier. The FE results can predict the characteristics of nonlinear structural collapse at both the local panel and the global hull girder levels. The collapse behaviour includes the reduction of the carrying capacity and the unloading of the recovered path, and the main purpose of calculation of the unloading path in the FEA is to find the unloading point related to the extent of collapse of the hull girder when it is subjected to extreme loads. This feature is available in ABAQUS by controlling the parameters in the loading step. Obtaining optimal values for the incrementation as well as the prescribed rotation of the end of the cross-section are highly important to control the convergence problem.

The simulation consists of two steps. In the first step, an elastic buckling analysis (also known as a linear perturbation analysis) was performed on a perfect cross-section of the bulk carrier to obtain the buckling mode (eigenmode), which indicates the possible buckling mode of the cross-section. In the second step, a nonlinear analysis was carried out on the FE model using the modified Riks method. The material plasticity strains is assumed to be elastic-perfectly plastic and the geometric imperfections which have a relative small effect on the ultimate strength were also included in this analysis to obtain the ultimate failure loads and failure modes of the bulk carrier.