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ScienceDirect
Composite Structures 77 (2007) 36–44
COMPOSITE STRUCTURES
www.elsevier.com/locate/compstruct

Longitudinal strength analysis of ship hulls of composite materials under sagging moments

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Available online 22 July 2005

Abstract

An approach to estimate the longitudinal strength of ship hulls in composite materials is presented in the paper. Typical ship configurations have as dominant failure mode the failure of the deck under compression associated with sagging moments. Ship hulls are modeled as assemblies of stiffened composite panels. Buckling, material failure and ultimate collapse of the stiffened panels are predicted by nonlinear finite element analysis, which is based on a degenerated three-dimensional laminated composite shell element with updated Lagrangian formulation and first-order shear deformable kinematics. According to buckling, material failure and ultimate collapse of stiffened panels, the corresponding longitudinal strengths of ship hull are derived from a simplified method. A ship hull under sagging is analysed as an example application.

Keywords: Stiffened composite panels; Ship hull in composite materials; Buckling; Material failure; Ultimate collapse; Nonlinear finite element analysis

1. Introduction

In recent years the improved design, fabrication and mechanical performance of low-cost composites has led to increase in the use of composites for large patrol boats, hovercraft, mine hunters and corvettes. Currently, there are all-composite naval ships up to 80–90 m long, and if this trend continues, Mouritz [1] predicted that hulls for mid-sized warships, such as frigates that are typically 120–160 m long, may be constructed in composite materials from 2020.

To ensure safe design of a ship's hull, traditionally, the longitudinal strength of the ship hull built of steel with length exceeding 60 m must be assessed at design. The longitudinal failure of ship hulls in composite materials is usually easier taken place than hull girder built of steel with equivalent length because of relative low stiffness and relative thin structures. With the trend that the size of ship hull in composite materials is upon large-scale, it is becoming necessary to study the longitudinal strength of ship hull in composite materials.

Ship hulls in composite materials can usually be regarded as assemblies of a series of stiffened composite panels. Thus, knowing the strength of stiffened composite panels it is possible to estimate the longitudinal strength of ship hulls in composite materials.

Smith and Dow [2,3] investigated the compressive strength of hat stiffened GRP panels, both theoretically and experimentally. Structural tests were carried out on two large scale longitudinally stiffened GRP panels representative of ship's deck structure. The test results were correlated with theoretical predictions using folded plate techniques to predict initial buckling stresses and nonlinear finite element method to predict the nonlinear response and post-buckling behaviour of the panels. However the collapse strength of the two panels has

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doi:10.1016/j.compstruct.2005.06.002

not been predicted due to lack of rational failure criteria. Stevens et al. [4] presented both theoretical and experimental results for the post-buckling behaviour of flat, stiffened, carbon fibre composite panels under compressive loading. Nonlinear finite element methods were used to predict both the buckling and post-buckling response of the panels. A failure mechanism, involving stiffener debonding, leading to eventual collapse of the panel was identified and predicted using the finite element method. These results are useful to understand the behaviour of fibreglass panels under the same conditions.

Dow [5] presented the results of large and small-scale experimental investigations into the collapse performance of fibre reinforced composites for marine structures. In a number of cases the author used nonlinear finite element methods to correlate with the experimental data presented. Kim et al. [6] presented an analytical and experimental study into the post-buckling behaviour of stiffened composite cylindrical panels. They employed a progressive failure analysis method to predict the failure characteristics and post-buckling ultimate load within a layered finite element approach using a maximum stress failure criterion. Kong et al. [7] presented both theoretical and experimental results for the post-buckling behaviour of graphite–epoxy laminated stiffened panels by a progressive failure analysis method based on maximum stress criterion and the complete unloading failure model.

In general, the most effective method to estimate the strength of stiffened composite panels is the nonlinear finite element method and the progressive collapse analysis, which is usually based on material failure criteria and degradation models.

In order to evaluate the longitudinal strength of a ship hull several methodologies have been developed and set up on the basis of different approaches. Caldwell [8] was the first to introduce the concept of ultimate strength of the ship hull. He introduced the plastic collapse moment considering the influence of yielding of all structural members composing a ship's hull, subjected to a bending moment. In Caldwell's method, the ultimate hull girder strength is calculated without considering the strength reduction in individual members after they have attained their ultimate strength locally. In general, this does not represent the real collapse behaviour of the structural members, but it is a conservative prediction. For this reason, it is very important to take into consideration the strength reduction (load shedding) of each structural member when the collapse behaviour of a ship's hull is simulated.

Some numerical methods have been developed to take into account of the strength reduction of structural members after their ultimate strength as well as the time lag in collapse of individual members. Smith [9] proposed an approach in which the cross-section is divided into small elements composed of a stiffener and attached plating, and the average stress–average strain relationships of individual elements are derived before performing a progressive collapse analysis, which accounts for the contributions of all elements. While Smith's method was based on finite element results for each stiffened plate element, Gordo et al. [10] modelled this behaviour with simple analytical formulas and comparison with experimental work showed the adequacy of the method [11].

The research work that has been reported here on the longitudinal strength of ship hull girders was conducted on steel structures. For ship hulls in composite materials little work has been done on the study of the longitudinal strength, Chen et al. [12,13] proposed an analytical method to predict the longitudinal strength of a ship hull in composite materials, which is based on a simplified method to represent the behaviour of stiffened composite panels.

The structural behaviour of ship hulls in composite materials is commonly complicated by the anisotropic and brittle nature of the material. The Young's moduli of typical composite materials adopted in ship construction are usually much lower than that of steel, which implies that the deck or bottom of ship hulls may be liable to buckling. The typically brittle property of composite materials not only may induce the material failure of a local area in ship hull but also cause the residual collapsed strength of panels to be negligible.

Since the residual collapsed strength of panels is negligible, the collapse of one or two panels in deck may cause the collapse of whole deck because the deck and bottom of ship hulls are usually made of a series of similar panels, which will have similar strength against compressive loads, caused by hull bending. In general the bottom structure of the vessels is stronger than the deck because the location of tanks and of the support of the propulsion systems leads to the need of more material. This means that in general the weakest failure mode is the failure of the deck, which is the main concern of this paper.

Based on above basic idea and on nonlinear finite element analysis, a method for estimation of the longitudinal strength of ship hull in composite materials under buckling, material and ultimate collapse is presented in this paper.

2. Strength analysis of stiffened composite panels

In this section the method adopted for the estimation of buckling, material failure and ultimate collapse of stiffened composite panels is briefly described.

2.1. Finite element formulation

The incremental equations of a continuous medium are formulated based on the principle of virtual work,