Abstract of Dissertation

Title: Residual hull girder strength of asymmetrically damaged ships

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A ship's hull may suffer collision or grounding damages, which may threaten the safety of ships and the surrounding environment. In order to enhance the structural safety of ships and reduce the associated risks, International Maritime Organization (IMO) has required in the Goal Based Standard (GBS) for bulk carriers and tankers an assessment of the residual hull girder bending strength in the specified damaged conditions. A ship's hull has normally a symmetric cross section, and the neutral axis for vertical bending is horizontal and moves only vertically during the progressive collapse under bending. However, when the cross section is asymmetrically damaged, the neutral axis rotates about the longitudinal axis. This induces the larger stress and strain at the damaged side than the undamaged side. International Association of Ship Classification Societies (IACS) has launched a new draft common structural rule for bulk carriers and oil tankers, in which the residual hull girder bending strength is calculated assuming the horizontal neutral axis first, and then the calculated strength is reduced by 10% considering the effect of the rotation of the neutral axis. This constant reduction rate is, however, not reasonable as it varies depending on the location and extent of damages.

The primary objective of the present study is to develop a rational and simplified method to estimate the residual hull girder strength of asymmetrically damaged ships considering the effect of rotation of the neutral axis. The Smith's method, widely accepted for the collapse analysis of an intact hull girder under vertical bending, is applied and extended. The in-house code, HULLST, is used for the calculation of the average stress-average strain relationship of stiffened plate necessary for the Smith's method. The damage is modeled by simply removing the panel and stiffeners in the specified area. First, the collapse behavior is formulated as a biaxial bending problem considering the rotation of the neutral axis. For the assessment of the safety of damaged ships, not only the residual capacity of a damaged cross section but also the collapse behavior of a whole hull girder need to be predicted, including the scenario of a heeled condition due to flooding. A simple model to predict the damaged hull girder behavior under general loading conditions is developed introducing the Smith's approach to the conventional beam finite element. A closed-form formula of the reduction rate of the residual strength due to asymmetrical damage is presented. The obtained results are verified trough a comparison with the nonlinear Finite Element (FE) analyses. The main results and conclusions are summarized as follows:

(1) Residual strength of asymmetrically damaged cross section

The incremental formulation of biaxial bending collapse behavior of asymmetrically damaged cross sections is presented including the solutions procedures for the proportional biaxial moment loading as well as the proportional biaxial curvature loading. The average-stress for the case of subject ships, the effect of rotation of neutral axis on the residual hull girder strength is about 8% at maximum for bulk carriers and negligibly small for a tanker assuming the damage extent specified in IMO/GBS. The reduction rate given in the IACS draft rules is found to be on the conservative side. It is also found that the residual strength interaction relationship

obtained under the proportional moment loading almost coincides with that obtained by the proportional curvature loading.

(2) Residual strength and post-collapse behavior of asymmetrically damaged hull girder

The influence of the rotation of the neutral axis at the damaged part may be reduced by the presence of the adjacent intact part with no neutral axis rotation. To investigate the interaction effect between the damaged and undamaged parts, a hold model partially having an asymmetrical damage under vertical bending moment is analyzed. The computer code Beam-HULLST has been developed introducing the Smith's approach to the cross section into the conventional beam finite element. It has been found that the effect of the rotation of neutral axis on the residual strength is reduced when the constraint by the intact part is considered. It is also found that the post-ultimate strength is reduced more rapidly when plotted against the average strain of the damage hold than the average strain of the damage part. This is because of the localization of plastic deformation at the damaged part accompanied by the unloading at the undamaged part. The Beam-HULLST is effective for the post-ultimate behavior of the hull girder, which is necessary for a consequence analysis of damaged hull girder.

(3) Reduction rate of residual strength due to the rotation of the neutral axis under sagging condition

It is found from the progressive collapse analysis using HULLST or Beam-HULLST that the ultimate strength of asymmetrically damaged bulk carriers and tankers is attained when the deck part of the damaged part is almost fully collapsed. Based on the observation, a simple formula of the reduction rate of residual strength due to the rotation of the neutral axis is derived using the elastic cross sectional properties and the critical member strength. The predicted residual strength is found to be in good agreement with that obtained by the progressive collapse analysis.

(4) Comparison with nonlinear FE analysis

Progressive collapse analysis of a damaged hull girder is performed using the explicit shell FEM code. It is found from a comparison with the FE analysis that HULLST and Beam-HULLST give a reasonable prediction of the progressive collapse behavior. However, the residual strength predicted under the assumption of beam theory tends to be larger than the shell FE results, particularly when the damage is located on the compression side of hull girder bending. The need for the improvement of the estimate of the capacity at the damaged part has been remarked. The effect of the rotation of the neutral axis obtained by the FE analysis is smaller than that predicted by HULLST and Beam-HULLST. It is again shown that the neutral axis effect considered in the draft structural rules is over-pessimistic and more reasonable assessment can be made by the proposed approaches.