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A comparison of computational methods to predict the progressive collapse behaviour of a damaged box girder

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ABSTRACT

The progressive collapse of a box beam under longitudinal bending can be predicted using various computational approaches, including finite element methodologies and the simplified progressive collapse method. These methodologies are employed to complete a series of analyses on three small box girders. The models are first analysed in the intact condition and then several damage scenarios are investigated. The results from the different computational approaches are compared to determine their relative performance. The study demonstrates the significance of residual stresses that are created during the damage simulation and are represented using differing assumptions in each of the compared methodologies.

1. Introduction

A critical strength criterion for a thin plated box girder structure, such as the mid body region of a ship, is the ability to withstand combinations of vertical and horizontal bending moments acting upon the longitudinally continuous structure. The maximum capacity of a ship's hull girder under a pure longitudinal bending moment, normally referred to as its ultimate strength, can be determined using several numerical approaches which are generally referred to as progressive collapse analysis.

The ultimate strength of an intact ship is an important measure to ensure the structure will not collapse under maximum expected load scenarios. The ultimate strength is also increasingly used as a design factor for limit state analysis and is now a requirement in some classification rules. In addition to its intact strength, a ship structure may need to be assessed in various damaged conditions. If a portion of the longitudinally effective structure is ruptured or severely damaged through collision, grounding or malicious attack, the ultimate capacity will inevitably be reduced. An assessment of residual ultimate strength in a damaged condition is thus useful for determining recoverability, seaworthiness or assessing the capabilities of a particular structural arrangement for withstanding damage.

The results obtained from physical experiments provide an invaluable resource for validating theoretical modelling approaches and demonstrating how a structure behaves under closely controlled loading conditions. However destructive testing of large scale structures, such as ships and bridges, are normally limited by size and cost constraints. These factors have placed a great emphasis on developing robust theoretical techniques to examine structural characteristics such as ultimate strength and the effects of damage. In particular, the nonlinear finite element method (FEM) has become a dominant computational approach for complex structural engineering problems. However, the use of FEM opens many questions concerning how to best simulate specific load scenarios and also about the reliability of results from such complex analyses. A general purpose FEM package such as ABAQUS includes a range of different fundamental solution methods involving either static or dynamic equilibrium equations, and also has options to use different ways equilibrium is treated using either implicit or explicit convergence techniques. These approaches have particular advantages and disadvantages which affect their suitability for different problem types.

In addition to the complexities of the solution choice, FEM requires a rigorous definition of the material and geometric properties inherent in the structure, including an adequate representation of geometric imperfections and residual stresses. These parameters are especially critical for progressive collapse analysis, where a portion of the longitudinal structure is placed under in-plane compressive loading up to and beyond its buckling capacity. It is well known that the buckling strength of plates and stiffened panels are significantly affected by the magnitude, shape and distribution of imperfections.

The complexities of FEM in model setup together with the relatively expensive computation time means that there is a continued

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need for simplified analytical methodologies which are more time efficient and also provide a robust means of accounting for the nonlinearities associated with the buckling response. Therefore simplified methodologies can often be a more reliable choice for the structural engineer, depending on the type of problem and the context in which it needs to be solved.

The Smith progressive collapse method [1] is a widely known incremental approach used to predict the bending response of ship hull sections. The Smith method follows a fairly simple procedure, whereby the longitudinally effective structure is divided into elements, each element is assigned a load-end shortening curve and incremental curvature is applied at the instantaneous neutral axis. At each increment the in-plane displacement of each element is calculated and the cumulative response over the entire section is summed to calculate the incremental change in bending moment. The Smith method has been validated and shown to provide excellent results when compared to large and small scale sections [2]. The approach can also be used to predict the damaged strength of a girder, although the limiting assumptions of the method mean that only a relatively simplistic representation of the damaged area can be modelled.

Within the context introduced above, this paper provides a comparative assessment of several FEM and simplified approaches for the analysis of box girder structures in intact and damaged scenarios. The box girders replicate actual structures tested by Gordo and Guedes Soares [3]. In this study the girders are analysed in an intact condition and with ruptured penetrations to represent damage. Firstly, intact vertical bending moment tests are carried out and compared with the original physical experiments. The theoretical analyses are then extended to deal with biaxial bending. Comparative results are presented from implicit and explicit FEM together with simplified progressive collapse analyses. The theoretical analyses correlate very closely but there are significant differences in the prediction of ultimate strength compared to the physical experiment. A hypothesis to explain the discrepancy between results is demonstrated.

The use of FEM and simplified methods for determining the residual strength of box girders which have sustained damage is then investigated. Three severe damage scenarios are simulated using explicit FEM, and the ultimate strength of the damaged girder is then calculated using several techniques. The results demonstrate the significance of the residual stresses sustained in the damage simulation.

2. Progressive collapse experiments

Published research concerning hull girder progressive collapse mostly falls into one or more of three broad categories: reporting of physical experiments on box girders or ship structures; derivation of theoretical methods to estimate progressive collapse or ultimate strength; and results from theoretical modelling of sections using simplified and FEM approaches.

2.1. Physical experiments

Experimental data pertaining to global progressive collapse of ship structures is extremely limited, primarily because of the impracticalities and expense in testing large scale girder models in primary bending. Most experimental tests use relatively small box girder models, which are more easily tested within a laboratory. For example Reckling [4] carried out seven steel box girder tests, investigating their strength under pure vertical bending moment. Experimental box girder tests have also been completed by Dowling et al. [5], Ostapenko [6], Nishihara [7], Qi et al. [8], Akhras et al. [9], Gordo and Guedes Soares [10] and Saad-Eldeen et al. [11]. There are very few physical experiments which use actual ship structures. The only laboratory test result available in open literature is that of a 1/3 scale frigate model, which was loaded up to and beyond collapse under a vertical sagging bending moment [2].

Specific cases of actual ship's failures by a progressive collapse mechanism have also proved useful. One example is the merchant vessel Energy Concentration, which broke its back during loading in Rotterdam harbour. The incident provides a usable case study because the circumstances of the hull collapse were unusual. The hull girder broke in still water conditions and, furthermore, the loading condition at the time of the accident was known. Rutherford and Caldwell [12] used this information to calculate the applied bending moment at the time of failure. Equivalent calculations using the progressive collapse method correlated closely to the estimated actual ultimate strength of the hull.

This paper replicates experiments on three simple multi-frame box girder structures, which were originally physically tested at the Technical University of Lisbon (IST) using a four point bending rig as pictured in Fig. 1. The girders were built simply; because it is a small scale model the stiffeners are placed on the outside of the shell to enable welding access during construction. In total three girders were tested; all had the same longitudinal cross section (see Fig. 1) but with different transverse spacing between frames. The principal box girder dimensions are shown in Fig. 1 with spacing and thicknesses presented in Table 1.

Each test specimen length includes an additional 100 mm span at each end, which was connected to the bending rig by a heavy bulkhead. Load was applied through hydraulic jacks connected to a strong box, which in turn rests on the outer supports of the bending rig. All the supporting structure was constructed from thick high tensile steel. The test specimen was welded between the outer supports whilst the outer edges of the supports rested on the floor. The rig thus produces a four point bending load, with the central section under pure bending moment.

2.2. Simplified progressive collapse methods

Longitudinal progressive collapse involves nonlinear buckling and collapse of compressed portions of the box girder beam. Numerical tools of the hull girder and to assess the forces at which service, damage and ultimate limits are reached. These tools are also used to assess the strength of a structure after entering service, with specific considerations of damage or age related effects. A number of simplified progressive collapse approaches have been proposed and several continue to be developed. They range in complexity and include simple closed form empirical formulae [13], interframe progressive collapse methods [1] and compartment level methods [14]. The key methodology employed in this paper is the Smith method [1], which is one of the most well established simplified approaches to progressive collapse analysis.

The Smith method has three underlying assumptions: that plane sections remain plane, buckling of panels is interframe and that the behaviour of individual elements (described by load end shortening curves) can be treated in isolation. The assumption of interframe collapse means the method can be called two dimensional because only the longitudinal structural arrangement is considered.

The Smith method has been developed into various proprietary computer codes [15–19]. These codes use the same underlying methodology but differ in their approach to derive the load-shortening curves. For example, the UK MOD code NS94 [15] uses either a special purpose FEM program, FABSTRAN, to determine the load shortening curve for the plate-stiffener combinations. Later versions include simplified bilinear curve datasets which will provide a curve for a specific stiffened panel by interpolation.