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Numerical investigations of collision experiments considering weld joints

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ABSTRACT

The design of double hull structures is investigated through two collision experiments with different large-scale specimens. The experiments were performed with a design of a typical double hull structure and a design with an alternative stiffening system (English: plate strengthened stiffeners, German: Plattenverstärkte Profilsteifen – PVPS) invented by Röhr and Heyer (2007) [1]. In contrast to the typical double hull design the alternative stiffening system is characterized by an additional trapezoidal sheet metal which is welded on the bulb profiles of the outer shell. The focus of this investigation is to reproduce the experimental results in terms of the force–displacement curves and failure mechanisms in numerical analyses. For this purpose, true stress–strain relations are determined from tension and compression tests of the different steel batches and the weld metal of the large-scale specimens. The RTCL and Lou–Kõrgesaar–Romanoff failure criteria are calibrated using tension tests and applied to the numerical analyses of the experiments. Both failure criteria lead to nearly identical force–displacement curves as well as failure mechanisms and they are capable of reproducing the experimental results. In the finite element model, an analogous model of fillet welds is implemented by assigning a fictitious thickness and material behavior of the weld metal shell elements at the location of weld joints. It is necessary to consider weld joints with the analogous model in the numerical analyses to predict the maximum reaction forces in the force–displacement curves. Furthermore, the impact velocity in the numerical analyses is investigated and it is concluded that an impact velocity of 10 m/s is appropriate to balance the accuracy and the simulation time.

1. Introduction

Ship accidents due to grounding or collision led in the past to danger of human life and to environmental pollution because of oil or cargo leakage. Such accidents occur as a consequence of human failure as well as of technical failure in frequently used waters and coastal areas. Therefore, it is crucial to adopt measures such as the improvement of the crashworthiness to ensure the structural integrity of the ship. For that purpose several designs of double hull structures were invented in the past and two typical constructions are the X- and Y-core designs. They are characterized by x- and y-shaped core

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elements between inner and outer shell viewing on the cross section of a double hull structure. They are proven to increase the crashworthiness in several experiments and numerical investigations [3,4]. Another approach to increase the capability of a double hull structure to absorb energy is to fill it with filling materials like hollow glass spheres as reported by Schöttelndreyer et al. [5]. In the current study, a double hull design with the alternative stiffening system PVPS [1] (English: plate strengthened stiffeners, German: Plattenverstärkte Profilsteifen – PVPS) is investigated and compared to a conventional design. The double hull design with the alternative stiffening system is characterized by a trapezoidal sheet metal which is welded onto the bulb profiles of a conventional double hull design. Compared to other designs a double hull with the alternative stiffening system PVPS has the advantage of maintaining the manufacturing process of a conventional double hull and extending this process slightly by implementing a trapezoidal sheet metal. In addition, the double hull is accessible at any time for inspection.

Significant effort has been spent on numerical investigations of side shell structures focusing on the failure due to collision and grounding scenarios. Since numerical analyses of such scenarios are still challenging and related to uncertainties, various large-scale experiments are carried out to investigate the occurring failure mechanisms and to validate finite element models [6–10]. To predict failure in the numerical analyses several failure criteria are used. A simple way to predict failure is to apply a constant value of equivalent strain as fracture strain [11]. Several different authors showed that the fracture strain of ductile metals depend on the stress triaxiality which is calculated from the hydrostatic stress [12–14]. Common failure criteria, applied in numerical analyses of collision and grounding, depend on the stress state as the BWH (named after Bressan, Williams and Hill), the RTCL (named after Rice, Tracey, Cockroft and Latham) [7,8,10] and the Lou–Kõrgesaar–Romanoff [15] criterion. The BWH criterion is initially defined as a forming limit curve for sheet metal forming to predict plastic instability and is expressed in terms of the degree of biaxial straining. Applying an instability condition as a limiting curve for failure as the BWH criterion has the advantage of reducing the mesh sensitivity by avoiding the post necking zone. Furthermore, only the plastic behavior must be known to calibrate the criterion and no fracture experiment has to be carried out. The RTCL failure criterion is defined as a function of the stress triaxiality and is calibrated and adjusted to the element size by the fracture strain at uniaxial tension determined from tensile tests. The Lou–Kõrgesaar–Romanoff failure criterion is calibrated and adjusted to the element size by a tensile test as well. The adjustment to the element size is including a shape change of the function of failure strain, different than the calibration and adjustment procedure of the RTCL criterion.

Taking weld joints in numerical investigations of collision and grounding scenarios into account is rather uncommon. Peschmann [11] and Törnqvist [10] investigated numerically the fracture of fillet welds in longitudinal direction by studying the tearing experiment of Wang [16]. They used a modeling technique in LS-Dyna where weld joints are implemented through a constraint between a pair of nodes belonging to two different structural parts. The additional volume and the material behavior of the weld joint are not taken into account by the constraint. Failure in the weld joint constraint occurs when a limiting value for an equivalent stress σ_f is reached and whereupon the connection of the pair of nodes is released. The equivalent stress in the constraint is determined according to a design rule by the International Institute of Welding [17] from normal and shear stresses in the neighboring elements. Both authors concluded not to consider weld joints in numerical analyses of collision scenarios. They observed at different damaged ship structures through collision accidents that most of the weld joints remained intact because a significant overmatching of weld metals in steel ship structures compared to the base metal are typical. Furthermore, most of the energy is absorbed in the stiffened plates of the ship structure in a collision accident and not in the weld joints. Ehlers et al. [3] treated laser welds in a numerical investigations with LS-Dyna of a large-scale specimen with an X-core design as spot welds and used the same modeling technique of weld joint constraint as Peschmann and Törnqvist. They used an equivalent plastic strain ε_f as a limiting value for the constraint and showed the influence of the failure strain ε_f on the global response of the structure. Alsos et al. [7] investigated with large scale experiments grounding scenarios with unstiffened and stiffened plates. In numerical analyses of the experiments with an element size of 6 mm they implemented weld joints by applying an additional thickness to the elements at the intersection of plate and stiffener to reproduce the higher stiffenes in the weld joint and the strain concentration next to the weld joint in the plate before failure. The material behavior of the stiffener is applied to the elements at the intersection. Since the weld joints remained undamaged in the large scale experiments, there was no necessity for the numerical investigations to calibrate a failure criterion for the weld joint. In this study it was necessary to implement weld joints through an analogous model to reproduce the force–displacement curves and failure mechanisms of the two experiments.

2. Experimental investigation

2.1. Experimental setup and large-scale specimen of the collision experiments

The experimental setup of the collision experiments simulates the striking ship as a bulbous bow which penetrates the large-scale specimen perpendicularly (Fig. 1). Due to technical reasons, the collision test plant is laid out symmetrically and therefore the bulbous bow is designed as a rotationally symmetric body with high stiffness as compared to the double hull structure. The experiment was performed quasi-statically with a load velocity of 2 mm/s. The experiments were conducted in collaboration with the Hamburg University of Technology (TUHH) since the collision test plant is in Hamburg.

The large-scale specimen consists of a support-construction, which transmits the reaction forces occurring during the experiment on to the collision test plant (Fig. 2). The support-construction is made out of shipbuilding steel grade A36