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Habilitation

Ultimate Strength Assessment of Ship Structures

Summary (Theses)

The objective of this postdoctoral thesis is to demonstrate the applicability of feasible methods to determine the ultimate strength of plate, model and ship structures for different load cases. The simplified Smith's method, the Idealized Structural Unit Method (ISUM) and the Finite Element Method (FEM) are used to determine the progressive collapse behaviour of different ships in bending. The effect of welding related imperfections on the progressive collapse behaviour of the different steel structures is analysed. Appropriate approaches to model welding residual stresses as well as initial deflections of plates and stiffened plate panels are applied successfully. The main findings of this study can be summarized by the following theses:

(1) For the investigated rectangular plates under longitudinal thrust, the buckling mode is still present at ultimate strength but in the post-ultimate strength range the collapse mode is characterized in most cases by localization of plastic deformations. This behaviour can be simulated by ISUM with reduced numerical efforts compared to nonlinear finite element analyses (FEA). The influence of welding residual stresses on the reduction of the ultimate strength becomes more important when the plate slenderness ratio increases.

(2) Continuous plate and stiffened plate models are used to simulate the collapse behaviour for combined load cases of lateral pressure, inplane shear and longitudinal thrust. For higher water heads the ultimate strength is reduced significantly because the collapse behaviour changes to an interactive plate/stiffener collapse mode, which cannot be simulated by the continuous plate model. Therefore, too high ultimate strength results are determined by ISUM and FEM for the continuous plate model compared to the stiffened plate model. Inplane shear and welding residual stresses further reduce the maximum load carrying capacity for the different plate structures due to longitudinal thrust. In most cases the applied closed form formulae deliver higher ultimate strength results compared to the proposed numerical models.

(3) For the investigated rectangular plates under transverse thrust, buckling and initial yielding are observed until ultimate strength is reached. A cylindrical collapse mode develops, which is still present in the post-ultimate strength range. This behaviour can be simulated by ISUM with reduced numerical efforts compared to nonlinear FEA. Similar ultimate strength results are determined for the different plate structures, but nonlinear FEA tends to determine slightly higher ultimate strength results for the most plate structure models.

(4) Continuous plate and stiffened plate models are used to simulate the collapse behaviour for combined load cases of lateral pressure, inplane shear and transverse thrust. The collapse mode changes to a clamped mode for increasing water heads. The ultimate strength is reduced slightly but similar results are determined by ISUM and nonlinear FEA. Inplane shear and welding residual stresses slightly reduce the maximum load carrying capacity for the different plate structures due to transverse thrust. For all investigated cases the applied closed form formulae deliver higher ultimate strength results compared to the proposed numerical models.

(5) Progressive collapse analyses are successfully performed for a stiffened plate under combined loads of lateral pressure, inplane shear and biaxial thrust. Loading paths and interaction curves determined by the combined ISUM-plate/beam-column element model are very similar compared to nonlinear FEA. The applied closed form formulae deliver higher ultimate strength results compared to the numerical models when transverse thrust is dominant. A slight reduction of the load carrying capacity is observed when welding residual stresses are considered as well as for combined load cases of inplane shear and biaxial thrust.

(6) For further validation, the proposed ISUM-plate/beam-column element model as well as the FE model are applied to determine the collapse behaviour of different model structures in vertical bending. A box girder specimen and a 1/3-scale Leander class frigate model are analysed assuming an elastic-perfectly plastic material behaviour for all structural members. Initial imperfections due to welding are considered and special attention is given to welding residual stresses. The numerical results are validated successfully against experimental data. The application of ISUM to determine the ultimate strength of the proposed model structures in vertical bending is related to reduced numerical efforts compared to nonlinear FEA.

(7) A combined ISUM-plate/beam-column element model and a finite shell element model are developed to perform progressive collapse analyses of a box girder specimen in four-point bending. Compared to the experimental data the ultimate bending moment of the box girder specimen is determined for both numerical models with high accuracy, but for ISUM if not only initial deflections but also residual stresses due to welding are considered. The proposed concepts to impose welding related imperfections are well applicable. The initial bending due to the structural weight of the box girder is also considered to determine the maximum load carrying capacity. The post-collapse behaviour of the specimen is simulated well by nonlinear FEA instead of ISUM due to specimen dimensions and properties.

(8) A combined ISUM-plate/beam-column element model and a finite shell element model are developed to perform progressive collapse analyses for a 1/3-scale Leander class frigate model in sagging condition. Compared to the experimental data the ultimate bending moment of the frigate model is overestimated by ISUM and slightly underestimated by nonlinear FEA when only initial deflections, but no welding residual stresses are considered. The proposed concept to impose welding residual stresses is demonstrated exemplarily for ISUM. This model delivers very good results and slightly overestimates the ultimate bending moment because lower welding residual stresses are determined compared to the measured data. The post-collapse behaviour of the specimen is simulated well by ISUM and nonlinear FEA.

(9) Different numerical methods are successfully applied to determine the progressive collapse behaviour of a container vessel, bulk carrier and double hull VLCC in bending. Smith's method, ISUM and FEM are used to determine the ultimate hull girder strength in vertical, horizontal and biaxial bending for intact and damage conditions. The influence of material properties and welding related imperfections on the ultimate strength are investigated. Special attention is given to welding residual stresses.

(10) In the framework of Smith's method, the modelling and computational efforts are very low compared to ISUM and nonlinear FEA. The cross section remains plain during the progressive collapse analysis and interaction of structural elements is not considered. In biaxial bending Smith's method most often delivers higher bending moments compared to ISUM respectively nonlinear FEA. Welding residual stresses are not taken into account.

(11) In the framework of ISUM, the modelling and computational efforts are much higher compared to Smith's method. The initial deflections are considered directly but the modelling efforts increase further when welding residual stresses are taken into account. The stiffeners are modelled with beam-column and the plating with ISUM-plate elements that the entire number of elements is much lower compared to the FE model. Therefore, the computational efforts can be reduced compared to nonlinear FEA.

(12) In the framework of FEM, all structural members are modelled with shell elements that all feasible collapse modes can be simulated. Initial deflections due to welding are given directly to the FE model so that modelling efforts are increased significantly. A simplified approach that welding residual stresses can be given directly to the FE model without changing the mesh is applied successfully. The progressive collapse behaviour of hull girders in bending can be simulated very well by fine meshed FE models but the computational efforts are much higher compared to Smith's method and ISUM.

(13) A deep neural network (DNN) is applied to estimate the moment-curvature curve and the shift of the neutral axis for ships in pure vertical bending. This approach might be useful for salvage operations, but the network still needs be trained with further results to improve its reliability.

(14) Finally, Smith's method is recommended to rapidly estimate the ultimate strength of intact and damaged hull girders in bending due to reduced modelling and computational efforts. ISUM is applicable to perform progressive collapse analyses of ships in bending more precisely taking welding residual stresses into account. Nonlinear FEA is recommended for a very precise prediction of the ultimate strength of hull girders in bending but related to higher modelling and computational efforts compared to Smith's method and ISUM. The effect of welding residual stresses on the progressive collapse behaviour of ships in bending is small but it is very important to apply the correct material properties and initial deflections due to welding for the different structural components.