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Compartment level progressive collapse strength as a method for analysing damaged steel box girders

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ABSTRACT

It is vital to be able to rapidly assess damaged ship structures. This ensures the safety of personnel and facilitation of the most effective repair or recovery. Interframe progressive collapse analysis has been used as a method for rapid assessment for vessels but its suitability for application to damaged vessels has been questioned, due to the limited failure modes assessed and modelling assumptions required when implementing the method. To reduce the cost and increase the effectiveness of the recovery of a damaged vessel, it will be important to more accurately assess the structure by determining the correct failure mode. This paper presents a study on the use of progressive collapse analysis to model damaged box girders which assesses the structure across multiple frame boundaries. The study shows that while progressive collapse analysis can be applied in the assessment of damaged box girders, implementing the newly proposed assessment allows greater accuracy in the calculation of the collapse strength through capture of the true mode of failure. This new method will allow the effects of the damage on surrounding structure to be captured which can influence the deflection shapes that will lead to collapse of the structure.

1. Introduction

Damage to ship structures can lead to unsafe conditions for crew and leave the environment at risk. Decisions to remain on board or vacate the vessel are often guided by shore based support services, undertaking calculations regarding the residual strength of the vessel. Once the vessel has been made safe it will be recovered or repair of the structure will start. During both stages accurate information of the ship's structure will be vital. Drawing on the similarities between ship hulls and box girders, this paper utilises a box girder arrangement to investigate the influence of a damage aperture on the ultimate bending strength of the structure.

Finite Element Analysis (FEA) can often be utilised to provide a comprehensive global bending strength assessment at either compartment or whole ship level but these methods tend to have long lead times. Due to the structural configuration, analysis of a vessel can be broken down into parts and made at different levels of detail using analysis methods such as progressive collapse developed by Smith et al. [1,2], Idealised Structural Unit Method (ISUM) developed by Ueda et al. [3,4] and ISFEM [5]. All three methods discretise the structural arrangement into sections of structure whose response is known, reducing the number of degrees of freedom and computational cost. Such methods allow rapid whole ship structural assessment to be performed but are constrained in the failure modes under which they can fail.

Inter-frame progressive collapse analysis developed by Smith and Dow et al. [1,2] is the most commonly implemented method within Naval Architectural Design and Classification Society Rules software used by emergency response services. This method maintains the assumption that inter-frame collapse is the prominent mode of failure of a longitudinally stiffened and transversely framed vessel, originally presented by Caldwell [6]. For progressive collapse analysis of ship hull structures, discretisation is commonly made into an assembly of plate-stiffener combination units [7] rather than the separate plate and beam-column elements commonly used in ISUM [8]. ISUM and ISFEM differ in that ISUM elements are solely based on analytical formulations or solutions, while ISFEM elements are formulated by taking advantage of both analytical solutions and Finite Element algorithms, which is considered to be more useful for modelling more complex structures [5]. The effectiveness of the ISFEM method is illustrated by Magoga and Flockhart [9] where it is used to model welding imperfections in aluminium craft allowing for the residual stresses, distortions and material softening to be taken into account.

Inter-frame progressive collapse analysis was first applied to the assessment of the residual strength of a damaged vessel by

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Smith et al. [2]. They conclude that in order to fully account for the residual stresses within a damaged structure, caused by the damage incident itself, it may be necessary to include a simulation of the damage process in any analysis of residual stiffness and strength, for example using dynamic FEA. Verification of the developed ship FE model is challenging, as experimental data is rarely available that is suitable for comparison, leading to the common reliance on simplified analytical or semi-analytical approaches. Whilst there are still relatively few experiments for verification these are increasing such as those by Gordo and Guedes Soares [10,11] who looked at box girders simulating compartment level studies in both high strength and mild steel. Tanaka et al. [12] provided experimental data at a considerably larger size performing three progressive collapse analyses at 1/13th scale showing the importance of initial imperfections under torsion, The results are compared to an FEA model which had a similar behaviour to the experiments but with a slightly higher ultimate strength. Iijima et al. [13] studied more realistic loading conditions by including the effects of whipping loads at 100th scale indicating these loads should be included in ultimate collapse strength analysis for accurate prediction. Despite the increase in the number of experimental cases the Smith interframe progressive collapse method is still commonly used as a verification tool for whole ship FE models. ISSC 2006 [14] presents a comparison of the ultimate strength of a cruise ship calculated by FEA with results of the Smith interframe progressive collapse method where the results can be seen to be up to 35.74% greater than the calculated FEA results for the same hull form, showing the interframe progressive collapse method to over predict the ultimate bending strength when compared to FEA. More recently, ISSC 2012 Ultimate Strength Committee [15] presented a benchmark study, the results of which are highlighted in Table 1. Similar variation can be seen in the results between users of the Smith interframe progressive collapse method as per the 2006 ISSC benchmark study [14] as well as variation in the results between users of the same and different FEA software. Discussion of the results suggests that some of the discrepancies encountered between FE users may be due to the different modelling approaches and the handling of further complexities such as initial imperfections and residual stresses [15]. A similar account is presented for the discrepancies between results from the Smith interframe collapse method [14], where the strength data for the stiffened-plate and hard-corner elements may be extrapolated from generic curves stored within the software or bespoke data calculated and input by the user before analysis. However, Paik et al. [7] provides a total of six possible failure modes that may exist when considering the failure of a grillage arrangement, whereby the "real ultimate strength is the minimum value of ultimate strengths obtained from the six solutions." [16]. These failure modes require analysis to be undertaken by more complex modelling techniques, such as finite element method (FEM), in order to tackle the problem as accurately and practically as possible,

Reviewing work done by other authors to investigate the residual strength of damaged ships, Das et al. [17] presents a procedure based on the Smith progressive collapse method to evaluate the residual ultimate hull girder strength of a damaged ship after collision or grounding. This paper concludes that the use of an incremental iterative approach, based on the Smith method, is adequate to estimate the ultimate strength of a damaged ship. They also conclude, as would be expected, that the structural arrangement of the vessel significantly influences the damaged hull ultimate strength and that the presence of damage will reduce the ultimate strength of the hull to an extent influenced by the prominent failure mode of the structure.

In relation to the location of damage and ultimate strength, Gordo et al. [18] conclude that the hogging moment is much more affected by bottom damage than the sagging moment and in a grounding scenario it is preferable to keep the ship in a sagging condition, as its ability to resist bending remains almost equivalent to intact. In their own work to investigate the residual strength of a damaged warship, Ren et al. [19] cite the Smith progressive collapse method as suitable for calculation of residual capability of a damaged ship. Shi and Wang [20] compared an experimental investigation into the ultimate hogging strength to FEA. A perfect model was used alongside one where initial imperfections were included with the initial imperfection model over estimating the ultimate strength by 2.3% and the perfect model showing similar slightly higher results with a 6.9% difference to the experiments. Simpler methods have also been developed for assessing the ships strength after damage; Qi and Cui [21] developed an analytical method and coupled this with an elastic-plastic method. Paik et al.

Table 1
(a) & (b) ISSC 2012 Committee III.1 benchmark study results comparison [9].

Method (Analyst)	Dow's Test Hull (MNm)		Container (GNm)		Bulk Carrier (GNm)	
	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
ANSYS (PNU)	11.235	10.618	6.969	6.951	17.5	15.8
ANSYS (ISR)	–	–	7.409	7.176	18.326	17.726
ABAQUS (CR)	12.357	10.708	7.664	7.631	18.396	16.855
Difference PNU – ISR (%)	–	–	6.3%	3.2%	4.7%	12.2%
Difference PNU – CR (%)	10.0%	0.8%	10.0%	9.8%	5.1%	6.7%
Difference ISR – CR (%)	–	–	3.4%	6.3%	0.4%	−4.9%

Method (Analyst)	D/H Suezmax (GNm)		S/H VLCC (GNm)		D/H VLCC (GNm)	
	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging
ANSYS (PNU)	14.066	11.151	17.355	16.179	27.335	22.495
ANSYS (ISR)	–	–	21.2	20.21	30.106	28.175
ABAQUS (CR)	16.16	14.258	21.86	20.625	31.006	24.995
Difference PNU – ISR (%)	–	–	22.2%	24.9%	10.1%	25.3%
Difference PNU – CR (%)	14.9%	27.9%	26.0%	27.5%	13.4%	11.1%
Difference ISR – CR (%)	–	–	3.1%	2.1%	3.0%	−11.3%