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.

Keywords

Ultimate Collapse Strength, Damaged Steel Structures, Box Girders, Finite Element Analysis

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 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] and [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. [22] revisited the Paik-Masour formula for ultimate strength and modified this to account for pure vertical bending moment which allows for a more accurate calculation of ultimate hull girder strength. Guedes Soares et al. [23] undertook an investigation into the accuracy of the Smith method. It was concluded that the results compared well against each other for both intact and damaged conditions. It was noted that the results from the Smith method were conservative in comparison to the finite element results for hogging by 29.3%. However, it was shown for the test case that the Smith method was not conservative for the sagging condition, calculating an ultimate strength 10% greater than that calculated by FEA, although no experimental work was done to assess the accuracy of either the FEA or analytical methods within the Guedes Soares et al. study [23]. The most significant recent development to the progressive collapse method is that made by Benson et al. [24, 25] to develop a method to undertake a compartment level assessment. The work recognises the need to potentially assess alternative failure modes to inter-frame collapse in relation to the strength assessment of lightweight aluminium structures. This work culminates in a comparison of the progressive collapse of damaged steel box girders presented in Benson et al. [26] who used orthotropic plate method to do multi-frame, compartment level, analysis which proved to be unsuitable for damage assessment. This research shows a verified FEA model of a simplified box

girder comparing this with results using the Smith progressive collapse method and indicates that the failure type was not always interframe.

From the review of whole ship strength, it can be seen that there have been many studies to investigate the intact bending and ultimate strength of a vessel as well as several investigations into the strength of damaged vessels. Most of these investigations are based around variations of the Smith progressive collapse method and it is this method that is most widely implemented in ship structural analysis software. However, there are some constraints associated with this method where research previously published by the authors, Underwood et al. [27, 28], has highlighted these problems. In particular the failure cannot always be assumed to be interframe and as such new methods need to be developed which can capture these failure modes. To overcome the assumption that failure is always by interframe collapse this paper presents the application of a new method utilising grillages as the structural unit for modelling damage. The study emphasises that using damaged grillage element strength data in individual load shortening curves is not practical; however, kriging can be used to reduce the number of cases to be assessed and capture the strength data for a broad range of damage conditions, as presented previously by Underwood et al. [29]. This allows assessment of the progressive collapse of the hull to be initiated by either interframe or overall collapse depending on the natural failure mode of the damaged structure. This paper uses assessment of a number of damaged box girders to demonstrate the requirement for the method and the benefits of being able to account for different failure modes in the assessment of damaged ship structures.

2 METHODOLOGY

Previous research studies have investigated the influence of damage on the collapse strength of steel-plated structures. Underwood et al. [29] propose that the progressive collapse method could be developed, using the response surface method kriging, to capture the strength characteristics of the damaged steel structure and can then be used to determine the failure load. An investigation into the ultimate collapse strength of damaged grillages has demonstrated the need to assess damaged structure at this level of idealisation due to the influence of the damage on the developing failure mode of stiffened steel structures [28]. It is proposed that progressive collapse assessment can be implemented at a multiple frame or compartment level by idealising the structure into grillage elements, with the damage strength characteristics efficiently developed through FEA and stored within the response surface. However, it is necessary to demonstrate that the new compartment level progressive collapse method incorporating grillage elements can be utilised for the ultimate strength assessment of damaged steel box girders, a common idealisation of ship cross-sections, before the method is developed and coupled with the response surface.

In this paper, a box girder FEA model is therefore developed and a damage aperture introduced into the upper section of the structure. A bending moment is then applied to the box girder that puts the

damaged section under compressive loading. Implementation of the compartment progressive collapse model in both the intact and damaged conditions uses a grillage element spanning the full length and width of the box girder model. This has allowed the results from the interframe progressive collapse method, using stiffened-plate elements, and compartment level progressive collapse method, using grillage elements, to be compared. To distinguish between the two methods, they are subsequently referred to as interframe progressive collapse and compartment progressive collapse. To fully assess the ability of the new compartment level progressive collapse method, assessments of the box girders were undertaken in both the intact and damaged conditions, and are presented below.

2.1 Review of new progressive collapse method

The existing method of assessment of progressive collapse analysis is undertaken by incrementally increasing the assumed structural deformation due to the applied bending load, from which the strains in each of the structural units throughout the model can be calculated and assessed against the pre-calculated stress-strain curves. When a unit fails it is removed from the analysis and the iteration continued until the overall ultimate collapse strength of the structure is calculated. As a stress-strain curve must be pre-calculated for each element in the structure, curves are only produced for intact elements and do not include damage due to the large number of curves that would be required to develop a library for all the possible permutations. Therefore, to model a damage scenario, all damaged or partially damaged structural units are required to be removed from the model prior to commencing the analysis.

For example, in the case of an intact stiffened panel containing three attached stiffeners, the plate-stiffener combination idealisation, is that of the sum of three individual plate-stiffener elements as shown in 1(a). Introducing damage to the same panel at a location between two stiffeners, though not damaging any stiffeners, the approximation is reduced to that of a single intact element, as shown in Figure 1(b). This assumption has to be made as the stress-strain curves cannot account for damage in the elements. Introducing damage to the panel, located such that it damages a stiffener, the structural idealisation approximation is reduced to that of two intact elements as shown in Figure 1(c). As can be seen from this example, the modelling of damaged structures is simplified, and can be represented by the formulation in Eq.1, where ‘ P_{u0} ’ is the ultimate collapse load of the structure, ‘ P_{ui} ’ is the collapse load of the intact structural idealisation elements (obtained from the pre-calculated stress-strain data) and ‘ n ’ is the number of intact elements. It is likely that formulation in this form will result in an overly pessimistic assessment of the residual strength of the structure by not accounting for the strength of the damaged elements.

$$P_{u0} = \sum_{i=1}^n P_{ui} \quad (1)$$

In order to be able to benefit from the rapid modelling capability of progressive collapse but be able to capture the damage to a stiffened panel and hence more accurately model the total structure, it is proposed that additional information is captured in relation to the collapse strength of the damaged panels and included in the formulation. This is achieved by modifying Eq.1 to include the damaged panel strength, as shown in Eq.2, where ‘ P_{ud} ’ is the collapse load of the damaged units (obtained from pre-calculated data) and ‘ m ’ is the number of damaged elements.

$$P_{u0} = \sum_{i=1}^n P_{ui} + \sum_{d=1}^m P_{ud} \quad (2)$$

2.2 Grillage FE Model Definition

To capture the influence of damage across multiple frame bays, the proposed unit to be utilised within this methodology is a grillage. In all cases analysed here, the arrangements feature four regularly spaced identical longitudinal stiffeners and five deeper orthogonally connected equally spaced transverse stiffeners. The grillage is assumed to be bounded at its transverse ends by deep frames or bulkheads which are assumed to remain plane and along its longitudinal edges by further grillage structure. The loading condition for the grillage is an in-plane compressive load along the length of the longitudinal stiffeners until the panel is unable to support any further load, at which point the ultimate compressive strength can be calculated. The load has been applied to the grillage in the form of a stepped displacement of the loaded edge.

Zhang et al. [30] present data relating to the plate slenderness ratio (β), Eq.3, and column slenderness ratio (λ), Eq. 4, for structure within the midship region for a total of 22 oil tankers and bulk carriers. This shows that the slenderness ratio encountered within these arrangements is between 1.0 and 2.5 and column slenderness of 0.2 to 1.0. Although these values push the boundaries of likely structure to be found within commercial ship and offshore structures, analysis has been undertaken of four grillage arrangements of plate slenderness ratios 1, 2, 3 & 4 to account for arrangements that may be used in other applications. This is achieved by varying the longitudinal stiffener spacing whilst maintaining a constant plate thickness. In all cases the Indian Standard Angle stiffener profile ISA70456 was used for all longitudinal stiffeners and Admiralty T-bar Type 2, 4.5”, whose dimensions are shown in Table 2, with attached plate of constant thickness of 6mm. This leads to column slenderness ratios of 0.61, 0.66, 0.67, 0.68 for each arrangement respectively, maintaining a transverse stiffener spacing of 1500mm in all cases.

$$\beta = \frac{b}{t} \sqrt{\frac{\sigma_y}{E}} \quad (3)$$

$$\lambda = \frac{L}{r\pi} \sqrt{\frac{\sigma_y}{E}} \quad (4)$$

In the above relationships, ' σ_y ' is the Yield Stress of the material, ' E ' is the Young's Modulus, ' b ' is the panel breadth or longitudinal stiffener spacing, ' t ' is the plate thickness, ' L ' is the panel length or transverse stiffener spacing and ' r ' is the radius of gyration based on the effective width of attached plate.

The modelling arrangement and boundary conditions used within the FE modelling have been created drawing on previous work undertaken by the authors to model damaged stiffened panels [27, 28, 29 and 30] and guidelines for the use of FEA for the ultimate strength assessment of stiffened panels [32, 16 and 33]. All FEA has been undertaken using the commercial FEA software ANSYS v14.0.

Modelling of the stiffened plate structure has been undertaken using the ANSYS 4-noded, quadrilateral, isoparametric shell element SHELL181 [16]. The element is suitable for undertaking the analysis of large strain non-linear plate structures and is capable of including membrane and bending stresses as required by this study. The element itself has six degrees of freedom at each node (UX, UY, UZ, ROTX, ROTY, ROTZ). Within the area of structure immediately surrounding the damage aperture, the triangular form of the SHELL181 element has been used as a filler element. This approach is recommended by the software developers and previously employed by the authors in prior damaged plate studies [27, 28, 29 and 31] and Suneel Kumar et al. [34] on the effect of circular openings on the strength of stiffened-plate structure.

In all cases a grillage arrangement incorporating an additional half stiffener spacing of plating between the edge and nearest longitudinal stiffener has been included along the simply supported longitudinal edges. Along the loaded ends, a full stiffener spacing has been included between the edge and nearest transverse stiffener and a clamped boundary condition applied to simulate connection of the grillage to stiffer structure, for example bulkhead or deep frames, at each end. On the loaded edge, an additional coupled constraint equation is applied to ensure the load is applied uniformly across the end. Figure 2 shows the applied constraints for all cases on an example damaged grillage arrangement.

In the assessment of stiffened panels under axial compression undertaken by Cetena S P A for the ISSC 2009 Ultimate Strength Committee [35], it has been shown that the material model used can influence the predicted ultimate collapse strength of the panel by allowing or restricting strain-hardening of the model. Whilst it is shown that the inclusion of strain hardening leads to an increased ultimate collapse strength of the panel due to increased stiffness, the modes of failure do not change. Therefore, throughout this study, no strain hardening has been included in the applied material model through utilisation of an elasto-perfectly plastic stress-strain relationship, so as to provide a conservative prediction of the ultimate collapse strength. A Young's Modulus of 211GPa, Poisson's Ratio of 0.3 and Yield Stress of the material of 745MPa are used throughout the study.

2.3 Box Girder FE Model Definition

To compare to the new progressive collapse method a box girder model has been created. Recently a number of box girder ultimate bending strength experimental tests have been performed by Gordo et al. [36,11] and Saad-Eldeen et al. [37,38,39]. Due to the extents of the model, which span multiple frame bays, and the lack of corrosion within the model, the Gordo et al. high tensile steel box girder model [31] was selected for development and verification of a box girder FE model. Development of the model also benefited from work presented by Benson et al. [26] who modelled this same box girder arrangement using the commercial FE software ABAQUS, and investigated the boundary conditions being applied to the box girder by the test rig. The work by Benson et al. [26] also included the assessment of one of the box girder arrangements by interframe progressive collapse, which has been used for the verification of the tool developed by the author.

In their work, Gordo et al. [11] performed ultimate bending strength experimental tests on three box girder structures manufactured out of high tensile steel with Young's Modulus 211GPa, yield stress of 745MPa and Poisson's Ratio 0.3. The dimensions of the box girders are 800mm breadth, 600mm depth with a thickness of 4mm and stiffener dimensions which can be seen in Table 3.

The FE modelling of the box girders utilises an elasto-perfectly-plastic stress-strain relationship and is suitable for obtaining ultimate bending strength data, though they may lead to a conservative calculation of the post collapse region. The box girder has been modelled using the ANSYS shell element SHELL181. This is the same element that has been used in the previous study by Underwood et al. [27] and for the grillage analysis and is suitable for this type of application where large structural distortion and non-linear effects are expected.

Provided the experimental test rig has applied a pure bending moment to the box girder structures, it should not be necessary to model the entire test rig to replicate the results using FEA. Therefore the FE modelling has only replicated the box girder structure with suitable boundary conditions. It is desirable to assess the structure under pure free bending, as the loading form applied to ship structures when at sea.

Application of the boundary conditions and load to the FE box girder model must ensure overall stability of the model whilst applying a load that allows application of the required pure bending moment. The modelling must also account for the shift in neutral axis that will occur as the structure progressively fails. The boundary conditions discussed by Hughes et al. [5] have been applied to ensure these conditions are met. Therefore, one end of the box girder has been fixed using a clamped boundary condition, whilst the nodes on the other end have been tied to a single reference node using the ANSYS rigid beam element MPC184. The rotational displacement to induce the desired bending moment is then applied to this reference node. The rotational point is located on the transverse centre line of the box girder, at a vertical position equal to 1/5 of the total height of the box. The vertical height of the point is arbitrary and does not affect the solution obtained provided the point is allowed to freely translate as the rotational displacement is applied. However, the reference node was positioned such that the neutral axis would be expected to remain above it during the complete solution. The applied boundary conditions can be seen in Figure 3.

2.4 Initial Imperfection Definition

In total, three forms of initial imperfections are seeded into both grillage and box girder models to account for the potential failure modes in the plate and stiffeners. These are plate vertical imperfection (w_{opl}), stiffener column-type vertical imperfection (w_{oc}) and stiffener sideways imperfection (w_{os}). Application of the imperfection modes of failure is commonly achieved through the use of a Fourier series as shown in Eqs.5-7.

$$w_{opl} = \left[\sum_{i=1}^m A_{om} \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{\pi y}{b}\right) \right] w_{oplm} \quad (5)$$

$$w_{oc} = \left[\sum_{i=1}^n A_{oi} \sin\left(\frac{i\pi U}{a}\right) \right] w_{ocm} \quad (6)$$

$$w_{os} = \left[\frac{W}{h_w} \sum_{i=1}^n A_{oi} \sin\left(\frac{i\pi U}{a}\right) \right] w_{osm} \quad (7)$$

where A_o is the coefficient of the initial deflection shape, m and i are the mode shape number, a and b are the plate or stiffener length and plate breadth respectively, x and y are the location along the length and across the breadth of the plate respectively, U is the position along the length of the stiffener and w_{oplm} , w_{ocm} , w_{osm} are the maximum imperfection values for each imperfection type.

These are seeded into a grillage FE model using average imperfection levels as detailed in Table 4.

To aid convergence of the solution where required, a stabilisation energy coefficient was included within the ANSYS solution phase. This stabilisation coefficient is described within the ANSYS structural analysis guide [40] and referred to as the energy dissipation ratio, and defined as the ratio of work done by stabilising forces to element potential energy, and having a value between 0 and 1. However, application of this factor can influence the results by artificially stiffening the structure. To ensure the results obtained are not being influenced by the level of stabilisation energy being applied, the total stabilisation energy was kept below 1% of the total potential energy in the structure, in accordance with the ANSYS structural analysis guide [40].

3 VERIFICATION OF INTACT BOX GIRDER ASSESSMENT

3.1 Mesh Verification

Verification of the FEA box girder model using ANSYS has been undertaken by modelling the Gordo et al. [11] H300 and H400 test cases. In his work to recreate the Gordo et al. [11] box girder experimental tests using FEA, Benson [24] performed the analysis, using ABAQUS FEA software, under pure bending as an isolated box girder in the same manner described above, as well as modelling the box girder within the test rig. The results showed significant discrepancies between the isolated box girder and the experimental test results. Benson hypothesised that an additional constraint was being applied to the box girder by the test rig due to the application of the bending load. By replicating this additional constraint, through the use of a nonlinear spring, good correlation between the FE and experimental results can be seen for the H200 and H300. For the H400 case the ultimate bending strength correlates well between the FEA and experimental results, with and without the application of the nonlinear spring boundary condition, the initial stiffness appears quite different. As the development of the box girder for use within the research presented in this paper surrounds replication of the free bending of a ship hull, the attempt to recreate the Gordo et al. [11] experimental test results by application of additional boundary conditions is not recorded here. Furthermore, the study by Benson [24] demonstrates the complexities of verifying against experimental results by adapting the boundary conditions, against which good results have been obtained. Instead, due to the lack of available experimental results replicating the free bending condition, verification has been attained through comparison with the free bending FE results presented by Benson [24] in conjunction with analysis by interframe progressive collapse method using a progressive collapse tool developed by the author.

A convergence study of the mesh size within the box girder FE models was undertaken by solving a number of cases using different element sizes of average element edge length of either 20mm, 10mm or 5mm, the results for which can be seen in Table 5 to Table 7. From the box girder definition in Table 3 it can be seen that the longitudinal stiffener height is relatively small at only 20mm. However, the expected element edge length expected to provide sufficient accuracy of the overall model could lead to the stiffener being defined by only one or two elements. In the regions of the box girder under compression, a significant amount of distortion of the longitudinal stiffeners is expected, and such a coarse mesh in these areas could lead to solution issues. Therefore, regardless of element edge length, the longitudinal stiffeners were defined with 6 elements within the height. This level of division is believed sufficient to allow accurate modelling of the stiffener deformation. The results show good convergence for both models using an element edge length of 10mm. This also provides a suitable solution time for completing the analysis. It can be seen that an energy dissipation ratio of 0.015 was applied to the H300 box girder, leading to a maximum stabilisation energy level of 0.9% of the total potential energy of the system. The ratio used is believed to be acceptable in accordance with the ANSYS user documentation [40], and was required to ensure the solution progressed past the first failure point of the section whilst minimising the amount of artificial stabilisation energy within the model. No stabilisation energy was required to aid the solution phase of the H400 box girder cases.

The results of the intact H300 and H400 box girder assessments can be seen below in Figure 4, Figure 5 and Table 8. Both sets of results show the ANSYS FEA to be stiffer in the initial elastic region than the ABAQUS FEA which is believed to be due to neglecting of residual stresses in this model which were included in the Benson model. However, it matches well with the interframe progressive collapse analysis of the box girders. The H300 box girder results show suitable correlation with the ABAQUS results, and comparable to the variation demonstrated by the ISSC 2012 Ultimate Strength committee [15] bench mark study discussed earlier. Good correlation with the interframe progressive collapse analysis is also demonstrated with the H300 ANSYS FEA.

The H400 box girder results show a larger variation between the ABAQUS and ANSYS FEA; however, this is still within the possible levels of variation demonstrated in the ISSC 2012 Ultimate Strength committee [15] bench mark study. Whilst the initial stiffness matches well with the interframe progressive collapse assessment, the ANSYS FEA reaches a much earlier first failure point, which leads to a lower prediction of the ultimate bending strength by FEA. Whilst it is unclear why these discrepancies arise, it is believed that the ANSYS FEA solution is operating correctly and is suitable for use within the research study presented later in this paper.

Potential sources for differences in the results could be the FEA solvers or solver algorithms being used by the different software, it is possible that differences such as initial imperfection definition approach and the exclusion of residual stresses within the ANSYS FEA could account for this. ABAQUS uses the RIKS solver applying ARC Length method, which is generally assumed suitable for collapse analysis. Whilst ANSYS has this solver available, it is not possible to use it in conjunction with the MPC184 rigid beam element type used to apply the bending rotation. Therefore, the ANSYS Sparse solver has been used, applying a rotation to the reference node and using stabilisation energy within the solution phase. This approach is also considered suitable for this type of analysis [40].

3.2 Comparison of Intact Box Girder Models

Figure 6 and Figure 7 show a magnified displacement plot of the developed failure mode in the grillage element for the H300 and H400 box girders respectively. These demonstrate the interframe collapse nature of the arrangements in the intact condition, which matches with the same failure mode type as seen in the box girder analysis, Figure 8 and Figure 9. However, whilst the vertical direction of the displacements for the H400 grillage and box girder models match, the displacements of the H300 models do not. Figure 6 shows how the failure mode displacements are all in the same direction across the grillage, unlike the alternating mode seen in the box girder in Figure 8.

As can be seen from the results for the H300 box girder assessment in Figure 4, whilst the initial stiffness in the elastic region matches well between the compartment level progressive collapse assessment, the ANSYS FEA and interframe progressive collapse analysis, the ultimate strength prediction is much greater than both methods, at 16.9% and 19.3% respectively. Whilst the initial stiffness is different to the ABAQUS FEA undertaken by Benson [24], the ultimate strength is much closer, though still greater by 4.9%. This difference in stiffness may come from the consideration of the boundary conditions used.

It is believed that the increased ultimate bending strength predicted by the compartment level progressive collapse method may arise due to the strength data provided by the grillage FEA model. It is noted above how the failure mode displacement direction seen in the grillage element in Figure 6 is different to that seen in the box girder; where, for the grillage, the displacement is in a single direction across the structure, whilst the box girder shows an alternating displacement form.

Imperfections in the plate and stiffeners depend upon the production method, constraints and location of the stiffener but when modelling ship structures the most common initial imperfection shape is the “hungry horse” form, recommended by the ISSC 2012 [15], whereby the vertical initial imperfection direction in the plates and stiffeners is the same across the structure. This is the form of initial imperfection shape that has been applied to the grillage FEA model. In the study presented in Underwood et al. [28], the resulting failure modes in the grillages were seen to be of an alternating direction as has been seen for the H400 grillage in Figure 7. Investigating the development of the H300 grillage failure mode shows how the initial imperfection shape is stable as the axial load is applied, leading to the failure developing with deflections in the same direction between stiffeners. It is believed that this has led to a stabilisation of the developing failure mode, and a higher ultimate strength than would be achieved by an alternating deflection shape. This correlates with the findings of Nikolov [41], where it was shown that the stabilising effect of imperfections in stiffened steel plates could lead to an increased ultimate strength under axial compressive load.

The results in Figure 5 and Table 8 for the H400 box girder assessment show good correlation between the ultimate strength calculation by the compartment level progressive collapse method with the interframe progressive collapse method and ABAQUS FEA undertaken by Benson [24]. Comparison with ANSYS FEA shows a difference of 14%. It can also be seen that the initial stiffness of the compartment level progressive collapse method matches closely to the ABAQUS FEA results. The results compare more closely to the interframe progressive collapse method in this case, where the failure mode deflection in the grillage can be seen to match that of the box girder FEA, Figure 7 and Figure 9. It is noted that the compartment level progressive collapse method over predicts the failure compared to the ANSYS FEA box girder model by 14.7%. This is similar to the difference of 16.2% seen between the methods seen for the H300 box girder.

Whilst the variation between the results provided by the different analysis methods for the H300 and H400 box girders may appear large, they all fall within the potential variation trends demonstrated by the ISSC 2006 and 2012 ultimate strength committee bench mark studies [14, 15].

The intact box girder models have been verified against existing literature and experimental test cases to provide sufficient confidence in their assessment of the ultimate collapse strength. The verified cases have been created through the use of a tool developed by the author to create the ANSYS APDL code to generate and solve the FE models. Therefore, the developed tool is considered to be creating the models in the desired manner and is suitable for use within the damaged structural studies presented. Despite the variations demonstrated between the reference models, the box girder FEA model results provide sufficient confidence in the operation of the model, which is believed suitable for use within this study.

4 DAMAGED BOX GIRDER ASSESSMENT RESULTS

To demonstrate the ability of the new compartment level progressive collapse method for use in a damage scenario, damage has been introduced into the upper section of the H400 box girder. Assessment has been undertaken through the analysis of two damage events introduced into the panel as diamond cut-outs, using the same method as in Underwood et al. [27, 28], ignoring any potential residual stresses caused by the impact and extra material as this is assumed not to affect the strength of the panel. The first is a small damage event positioned with its centre at the middle of the central stiffener with the breadth of the damage equal to the longitudinal stiffener spacing giving a damage area ratio of 0.3. The damage area ratio has been calculated as the ratio of area of plate removed to the area of plate for the intact panel, as shown in Figure 10. The second damage case maintains the same damage location and breadth, but increases the length to provide a damage area ratio of 1.9. This damages two transverse stiffeners in addition to the single longitudinal stiffener in the previous case, as shown in Figure 11. Figure 12 and Figure 13 show the equivalent damaged grillage elements for use within the compartment level progressive collapse analysis.

The results of the discussed damage cases are shown in Figure 14 and Figure 15 for damage case 1 and case 2 respectively. Comparison of the results can be seen in Table 10. It should be noted that as the two damage cases have been defined with the same breadth, the damage strength assessment by the interframe progressive collapse method is the same, as the interframe method is unable to account for the increased length of the damage seen in case 2.

The difference in results between the ANSYS compartment FEA and compartment level progressive collapse method is much closer for damage case 1 than was shown for the intact condition. However, the difference is 17.2% for case 2, which may be due to the modelling assumptions used in the grillage element not accurately matching the true structure. It should be noted that despite these discrepancies, the compartment level progressive collapse results proved to be conservative when compared to the ANSYS FEA in both cases. This contrasts to the interframe progressive collapse method which appeared to over predict the ultimate bending strength in both cases. The results show an over prediction of the damage strength of the structure by interframe progressive collapse in both damage scenarios when compared to the new compartment level progressive collapse method and ANSYS FEA, by 11.2% and 4.2% respectively for damage case 1, and 23.9% and 8.8% respectively for damage case 2. The method provides a compromise between computational speed and accuracy but importantly provides conservative estimates in both cases, and therefore has potential application within ship emergency response services where time and safety are critical.

Figure 10 and Figure 12 show the failure modes seen in the grillage and box girder FEA models respectively for the small damage. It can be seen that whilst the mode of failure in the two structures can be considered to be interframe in their form, the failure mode developed in the grillage model is more complex. It is believed that the connection of the upper grillage section to the side section, in particular the connection between the transverse frames, may be sufficient to prevent this mode of failure developing in the box girder. Therefore, further development of the grillage boundary conditions may be required to improve correlation and stiffen the current simply supported boundary condition on the longitudinal edges. However, due to the lack of availability of data against which to verify the suitability of any additional boundary conditions, which may lead to over-constraining of the model if not applied appropriately, additional boundary conditions have not been trialled within this assessment.

Figure 11 and Figure 13 show the failure modes of the second damage case within the grillage and box girder structures. The displacement plots show good correlation between the cases, both developing the same form which is no longer interframe. The results show that the grillage element can be used to capture interframe or overall collapse, whichever is the natural mode, including both transverse and longitudinal extents of damage and its influence on the failure mode. However, the extent of the deformation seen in the grillage model is greater than in the box girder FEA model. This again suggests that the simply supported boundary conditions on the longitudinal sides may be too soft and the connection between the side structures may need to be carefully considered in future analysis.

5 DISCUSSION

The implementation of the new compartment level progressive collapse method for use within intact and damage scenarios has been demonstrated. Whilst the results have shown good correlation with full section FEA in many cases, differences between the results of the method and those obtained by interframe progressive collapse and full section FEA have also occurred.

Reviewing the failure modes seen in the grillage element FEA, whose strength data is used by the compartment level progressive collapse method, and the full section FEA models, differences can be seen in the developing failure modes. In many cases the grillage model can be seen to be softer than the equivalent section within the box girder model, which may account for the conservative ultimate bending strength prediction in these cases. Conversely, where the developed failure mode in the grillage model may lead to an increased strength of the section, an over prediction of the ultimate bending strength can be seen.

In the assessment of a damaged box girder, the method has demonstrated its ability to account for the change in failure mode shape that may occur within this level of structural idealisation, providing a conservative prediction of the ultimate bending strength when compared to full section FEA. The identification of different modes of failure within a range of grillage arrangements is discussed in more details in Underwood et al. [28] which highlights results from a large set of analyses showing similar outcomes. The results of the analysis in this study contrast with the interframe progressive collapse assessment which over predicted the ultimate bending strength for the assessed damage cases. Furthermore this approach can capture the natural failure mode capturing transverse and longitudinal extents of damage, which hasn't been shown using other rapid analysis methods.

Whilst account for some potential discrepancies between the new compartment level progressive collapse method and full section FEA ultimate bending strength results has been made above, consideration must also be made regarding the idealisation of the new method. When undertaking interframe progressive collapse analysis, the longitudinal extent of the assessed section is short in comparison to the total length of the section or vessel. Therefore, it is appropriate to assess the strength of the individual stiffened-plate elements under pure compression. This same approach has been applied to the analysis of the grillage elements applied to the new compartment level method. However, this assumption may require further research to determine its appropriateness for damage calculations for example the initial imperfections have been scaled to the size of the panel and at a larger size may elicit a different behaviour in the failure. However, the same approach is taken in Benson and Soares and it is difficult to determine these effects without full scale experiments. When considering the loading of the compressed grillage section within the full FEA model, the loading cannot be considered to be pure axial compression in its nature. Therefore, more appropriate or representative loading may need to be applied to the grillage elements to ensure the most suitable strength data is generated for use by the method.

Application of the grillage element load may need to be approached in a similar method to that applied to the full section; by applying a rotational displacement to a reference node connected by rigid beam elements to the loaded end of the grillage. The positioning of the reference node will then be more critical than for the full section model, and should be located at the equivalent neutral axis position for the full section. It is recognised that as the full section progressively fails, the neutral axis position will move away from the failed sections. However, as the grillage elements are located furthest from the neutral axis within the modelled scenario, they would be expected to fail first before the neutral axis moves. When modelling a full ship section including deck structures, the influence of the shift of neutral axis on the grillage element loading may need to be considered.

Within the new method example cases presented, a grillage element has been utilised within the upper compressed section, whilst the side shell has been considered to continue to fail by interframe collapse. This can be seen to be an appropriate assumption by viewing the failure modes of the side structure within the displacement plots in Figure 8, Figure 9, Figure 12 and Figure 13. It is possible that the use of larger elements within the side structure may also be possible, and the influence of side shell damage from a collision event may lead to this interframe collapse failure mode changing. However, initial research from Downes et al. [42] indicates that this might not be the case. Idealising the side shell into larger element sizes adds additional complexity in relation to the application of the appropriate bending load across the structure. This will increase the complexity of the FEA but should not form any further issues for the methodology investigated here.

Whilst the potential of the new method has been demonstrated, it is clear that further development and understanding of the modelling of the grillage elements is required to ensure successful implementation. For application within an emergency response scenario, care must also be taken to ensure that the failure mode developed in the grillage does not lead to a best case scenario, from which the resulting decisions may endanger lives.

Due to the similarities between the implementation of the new compartment level progressive collapse method and the existing interframe progressive collapse method, the time to run the solution of the methods is equivalent. Due to these similarities and that using damaged grillage element strength data in individual load shortening curves is not practical it is also envisaged that this approach could be utilised alongside kriging models to develop metamodels of the data to be utilised for applications requiring rapid analysis whilst still allowing the ability to model the change in response mode. Therefore, with further development of the approach to implementation of the new method, it is believed that compartment level progressive collapse analysis can be incorporated within emergency response, salvage or early design.

6 CONCLUSIONS

The structural modelling of damage box girders can be important to increase safety and reduce repair costs. However, to ensure the safety the vessel structural modelling often needs to be performed rapidly. A number of methods are available for rapid analysis of intact box girders but damaged structures have more complex properties. This requires different modelling methods with the ability to assess multiple modes of failure to ensure the correct strength is calculated. Whilst a growing number of assessments look at compartment level structural analysis intact the difference in behaviour once damaged is reported less in the literature. This paper uses assessment of a number of damaged box girders to demonstrate the requirement for new methods and the benefits of being able to account for different failure modes in the assessment of damaged ship structures. A new modelling method, developed previously by the authors, has therefore been trialled in comparison to compartment scale. When applied to the assessment of damaged box girder structures, the method has shown to provide good, though conservative, prediction of the ultimate bending strength when compared to full section FEA and assessment by interframe collapse method. The method also demonstrated its ability to account for the reduced strength caused by the change in failure mode seen within the section of the box girder under compressive loading. Furthermore, this assessment can capture the damage event in both the longitudinal and transverse directions. This contrasts to the interframe progressive collapse method which was shown to over predict the damage strength when compared to full section FEA.

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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%

(%)						
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Table 2 Stiffener profile dimensions

Stiffener Profile	ISA70456	Admiralty T, Type 2, 4.5"
Overall Height (mm)	70	114.3
Flange Breadth (mm)	45	44.5
Flange Thickness (mm)	6	9.5
Web Thickness (mm)	6	5.1
Second Moment of Area (mm ⁴)	0.326x10 ⁶	1.263x10 ⁶

Table 3 – Box Girder Dimensions [20]

Box ID	Length (mm)	Frame Spacing (mm)	Longitudinal Stiffener Profile		Transverse Stiffener Profile			
			Height (mm)	Web Thickness (mm)	Height (mm)	Web Thickness (mm)	Flange Breadth (mm)	Flange Thickness (mm)
H200	100+4* 200+10 0 =1000	200	20	4	50	6	20	6
H300	100+3* 300+10 0 =1100	300	20	4	50	6	20	6
H400	100+3* 400+10 0 =1400	400	20	4	50	6	20	6

Table 4 – Maximum initial welding imperfection definitions for stiffened steel panels

	Smith [2]			ISSC [17]
	Slight	Average	Severe	
$w_{opl m}$	$0.025\beta^2 t$	$0.1\beta^2 t$	$0.3\beta^2 t$	$b/200$
w_{ocm} ($\lambda > 0.2$)	0.00025a	0.0008a	0.002a	0.0015a
($\lambda > 0.4$)		0.0012a	0.0038a	
($\lambda > 0.6$)		0.0015a	0.0046a	
w_{osm}	-	-	-	0.0015a

Table 5 – H300 Box Girder ANSYS FEA Results

Element Size	Energy Dissipation Ratio	Maximum Stabilisation Energy: Potential Energy	Maximum Bending Moment (Nm)	Time to Solve
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20mm	0.015	0.96%	8.56E+05	1 hour
10mm	0.015	0.90%	8.46E+05	3.5 hours
5mm	0.015	0.88%	8.42E+05	5 hours

Table 6 H400 Box Girder ANSYS FEA Results

Element Size	Energy Dissipation Ratio	Maximum Stabilisation Energy: Potential Energy	Maximum Bending Moment (Nm)	Time to Solve
20mm	0.00	0.00%	7.83E+05	1 hour
10mm	0.00	0.00%	7.79E+05	8 hours
5mm	0.00	0.00%	7.78E+05	>3 days

Table7 - Box Girder ANSYS FEA Results Comparison

Element Size Change	H 300 Difference in Max BM	H400 Difference in Max BM
20mm - 10mm	-1.21%	-0.52%
10mm-5mm	-0.39%	-0.20%

Table8 - Intact H300 Box Girder Ultimate Bending Strength Results

Method of Assessment	H300 Maximum Bending Moment (Nm)	H400 Maximum Bending Moment (Nm)
Gordo et al. Test	1.27E+06	1.02E+06
ANSYS Compartment FEA	8.42E+05	7.79E+05
Benson ABAQUS Compartment FEA	9.56E+05	9.57E+05
Interframe Progressive Collapse Analysis	9.04E+05	9.07E+05
Compartment Level Progressive Collapse Analysis	1.01E+06	9.13E+05
Difference Interframe Progressive Collapse Analysis – ANSYS Compartment FEA	-6.89%	-14.04%
Difference Compartment Level Progressive Collapse - ANSYS Compartment FEA	-16.21%	-14.68%
Difference Interframe Progressive Collapse Analysis - Compartment Level Progressive Collapse Analysis	19.34%	0.75%
Difference Interframe Progressive Collapse Analysis – ABAQUS Compartment FEA	5.71%	-0.06%
Difference Compartment Level Progressive Collapse – ABAQUS Compartment FEA	-4.87%	-0.05%

Table10 – Damaged H400 Box Girder Ultimate Bending Strength Results

Method of Assessment and Damage Scenario	Ultimate Bending Moment (Nm)
Interframe Progressive Collapse - Damage Cases 1 & 2	7.94E+05
Compartment Progressive Collapse - Damage Case 1	7.06E+05
Compartment Progressive Collapse - Damage Case 2	6.04E+05
ANSYS Compartment FEA - Damage Case 1	7.62E+05
ANSYS Compartment FEA - Damage Case 2	7.30E+05
Difference ANSYS FEA to Compartment Level Progressive Collapse - Damage Case 1	-7.42%
Difference ANSYS FEA to Compartment Level Progressive Collapse - Damage Case 2	-17.21%
Difference ANSYS FEA to Interframe Progressive Collapse - Damage Case 1	4.21%
Difference ANSYS FEA to Interframe Progressive Collapse - Damage Case 2	8.77%
Difference Interframe Progressive Collapse to Compartment Level Progressive Collapse - Damage Case 1	-11.16%
Difference Interframe Progressive Collapse to Compartment Level Progressive Collapse - Damage Case 2	-23.89%

Figure 1 – Structural idealisation approximation of a stiffened panel with three stiffeners - cross-section

Figure 2 - Example damaged grillage and applied boundary conditions

Figure 3 – Box Girder FE Model Applied Boundary Conditions

Figure 4 - Intact H300 Box Girder Ultimate Bending Strength Results

Figure 5 – Intact H400 Box Girder Ultimate Bending Strength Results

Figure 6 – H300 Upper Section Grillage Element Failure Mode – Magnified Displacement Plot

Figure 7 – H400 Upper Section Grillage Element Failure Mode – Magnified Displacement Plot

Figure 8 – H300 Failure Mode - Magnified Displacement Plot

Figure 9 – H400 Failure Mode - Magnified Displacement Plot

Figure 10 – H400 Grillage Element: Damage Case 1 Failure Mode - Magnified Displacement Plot

Figure 11 - H400 Grillage Element: Damage Case 2 Failure Mode Magnified Displacement Plot

Figure 12 - H400 Box Girder: Damage Case 1 Failure Mode - Magnified Displacement Plot

Figure 13 - H400 Box Girder: Damage Case 2 Failure Mode Magnified Displacement Plot

Figure 14 –H400 Box Girder Bending Strength Results – Damage Case 1

Figure 15 - H400 Box Girder Bending Strength Results – Damage Case 2