Collapse Strength of Intact Ship Structures

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Abstract: Ship structures are subjected to complex sea loading conditions, leading to a sophisticated structural design to withstand and avoid structural failure. Structural capacity assessment, particularly of the longitudinal strength, is crucial to ensure the safety of ships, crews, the marine environment, and the cargoes carried. This work aims to overview the ultimate strength assessment of intact ship structures in recent decades. Particular attention is paid to the ultimate strength of plates, stiffened panels, box girders, and entire ship hull structures. A discussion about numerical and experimental analyses is also provided. Finally, some conclusions and suggestions about potential future work are noted.

Keywords: intact plates and stiffened panels; box girders; ship structures; ultimate strength

1. Introduction

The hull girder capacity assessment concept has been transformed drastically as more insights have been collected about how ships respond to an externally applied complex load. Initially, the breaking strength was the criterion to assess a ship’s structural capacity. Still, it has evolved to include buckling strength. It later has moved into more sophisticated concepts involving the geometrical and material non-linearity of the structures, developing the ultimate strength or ultimate limit state criteria.

In the past, the criteria and procedures for the structural design of ships and offshore platforms were primarily based on the allowable stresses and simplified buckling checks for structural components. However, it is now well recognized that the ultimate limit state-based approaches are better suited for structural design and strength assessment than the traditional working stress-based approaches. The latter are typically formulated as a fraction of the material yield strength [1].

When it comes to the simple definition of the ultimate state, it is considered the stage where the ship structure cannot bear any further load increases and moves into its post-collapse or unstable phase. All the components that constitute the ship structure have their contributions to the ultimate strength. Each structural component, namely, stiffened plates or unstiffened ones, has its ultimate limit stages that add to the complexity of the ultimate limit state definition of a complex structure such as ships, which are composed of many components.

Many parameters influence the ultimate load carrying capacity of ship structures and range from the uncertainty of the materials that the ships are built of to the externally induced factors; namely, manufacturing defects that specifically involve welding-induced initial deformations and stresses, corrosion, fatigue-related cracks, the load that is acting on the ship’s structural components and their interactions, which are the bending moments and shear forces from a local and also global point of view, not to mention human error and poorly maintained on-board equipment, which lead to ship collisions and groundings, etc.
This review aims to provide a general overview of the work that has been performed over recent years, including on the strength of intact unstiffened plates or stiffened ones, box girders and finally, hull girders built of steel.

2. Plates

Plates are the main structural components in ship structures. They are subjected to a variety of external loads.

The load type that leads the plate to buckle, the compressive load, has been a study of interest because it involves unstable behavior and influences the safety of the hull girder [2]. Figure 1 shows the fundamental behavior of thin and thick plates under uniaxial compressive load. The buckling strength of the thick perfect plate is decisive in evaluating the collapse behavior that occurs in the plastic regime. However, for an ideal thin plate where the buckling occurs in the elastic regime, it does not indicate its true collapse strength since, after the buckling, the thin plate can carry a further load until the external load reaches the stage where the resistance of the plate supports no more load increases and the plate collapses and moves into its unstable stage.

![Diagram of Plate Behavior](image)

**Figure 1.** Fundamental behavior of plates under uniaxial compressive load.

However, in the case of typical ship plating, which is considered a thin or moderately thick plate, plate buckling generally does not occur in the critical sense due to the initial plate imperfections, and the deformations arise as soon as the load is applied. The plate carries the load until it collapses with a combination of buckling and plasticity. One of the primary failure modes of stiffened panels is the buckling and plastic collapse of the plates surrounded by the support members. Thus an evaluation of the plate buckling and plastic collapse behavior of the plates is essential in identifying the failure of ship structures [3,4].

2.1. Plate Collapse Assessment

Several design formulas have been presented under uniaxial compressive load over the years to predict the ultimate load carrying capacity of the intact plate components. The models proposed in [5,6] have been commonly used in marine structures. Frankland’s model is less conservative than Faulkner’s, which may be attributed to the assumed initial imperfections, boundary conditions or welding-induced stresses, an option for design approaches that prefer conservatism. These models predict a lower strength than the full plastic load, and this can be associated with the idea that only part of the plate is effective due to the buckling phenomenon, leading to a typical expression of plate effectiveness or effective width; that is, to reduce the strength of a plate by equating it to the strength of another plate that has an effective width and collapses at the nominal yield stress [7].
which is a function of plate slenderness, given the fact that plate slenderness is a critical indicator of plate strength.

As suggested by Guedes Soares [8], it is possible to conclude that the most straightforward design method should include only plate slenderness because plate strength can change by as much as 60% over the useful range of the slenderness. Suppose an improvement of the accuracy is desired: in that case, explicit attention must be given to the variables that can produce changes of 20% in the plate strength, the initial plate imperfections, welding-induced residual stresses, and plate boundary conditions. It was indicated that the plate aspect ratio is only relevant at low plate slenderness from 0.6 to 1.0 and leads to about 5% of plate strength. However, this is more appropriate when the initial imperfection shape is concerned. The type of loading is to be explicitly accounted for.

The plate strength approach, using the effective width accounting for the welding-induced residual stresses, was explicitly proposed by Faulkner [6]. That formulation has been extended to expressly account for the effect of initial imperfections [8]. However, considering that the main impact on the collapse strength depends on the plate slenderness and that the initial imperfections are random, only properly treated by probabilistic methods [9], alternative formulations to [6] have been proposed by Guedes Soares [2,10], which treat the initial imperfections in a probabilistic way and derive design equations only dependent on the slenderness instead of including the effect of residual stresses explicitly as in the Faulkner’s formulation, which incidentally covers both simply supported and clamped conditions. Carlsen [11], who also used the concept of the effective width given by a modified Faulkner’s formula, proposed other simplified formulations adopted by DnV at the time.

Instead of using the type of effective width formulation, Dwight and Little [12], and Little [13], preferred to use the effective yield stress associated with a Perry-Robertson formulation, which is a function of the breadth to the thickness that governs the plate strength. They also considered different classes of plate curves depending on the level of residual stresses.

The plate buckling strength under a uniaxial load is influenced by several external parameters, including manufacturing defects, initial imperfections, welding-induced stresses, and plate edge boundary conditions. It is essential to point out that some of the formulas presented were built to assume that the plate edges are simply supported. This can be justified, as indicated by Fujikubo and Yao [14]. In most cases, the increase in buckling strength due to the stiffness provided by the stiffeners around the plate is only slightly more substantial than the decrease due to residual welding stresses. The resulting elastic buckling strength is close to a simply supported plate with no residual stress for both longitudinal and transverse thrust cases.

The importance of the formulations of plate strength results from the fact that ship-stiffened panels are commonly designed so that the plate fails first, and only at a later stage does the total failure of the combination of plate and stiffener occur. As pointed out by Faulkner et al. [15], the inability of the structure to carry an additional load will be limited either by the panel collapse or by grillage instability in which the plate elements and stiffeners show unstable behavior together. Therefore, stiffened panel collapse is represented by the failure of the plate and stiffener together. The contribution of the plate after its failure to the stiffener must be quantified. An approximate incremental method was proposed to estimate the load-shortening curves of a stiffener assembly with associated plates, including the post-collapse behavior accounting for the initial imperfection and welding-induced residual stresses [7].

Several studies have attempted to estimate the plate’s average stress-strain relationship analytically by combining the larger elastic behavior of the plate with the rigid plastic method in the post-collapse region to determine the full load-shortening curves of the plates [16–19]. However, the analytical solutions are still to be improved because the ship plate collapse occurs in the plate elastic-plastic stage. It is also difficult to evaluate plate collapse involving complex failure modes under combined loading conditions.
It is challenging to formulate the non-linear governing equations representing both
the geometrical and material non-linearity for plating, although it is not impossible. A
significant source of difficulty is that an analytical treatment of plasticity with increased
applied loads is quite cumbersome. Even if such treatment were possible, it would not be
easy to solve the resulting non-linear equations analytically [20].

This approach was also adopted in a recent study performed in [21]. The solution of
combining the large elastic displacement with small strain analysis using the concept of
the principle of the virtual work is given for a uni-modal plate with initial imperfection
under uni-axial thrust if the initial imperfection shape does not alter. However, the mag-
nitude of the initial imperfection changes during external load exposure and the material
non-linearity is not considered given the small strain assumption. They also implemented
a simple solution to the post-collapse behavior of the plates using the concept of rigid
plastic material behavior with the Von misses yield definition (see Figure 2).

![Diagram](image)

**Figure 2.** (a) Normalized strength and mid-plate vertical displacement, \( W_v \), relationship; (b) simple rigid plastic solution.

### 2.2. Impact of Initial Imperfection

When a plate with initial defects and local bending stresses due to the initial defects
and welding-induced stresses is subjected to thrust, it reduces the plate rigidity and ulti-
mate load capacity [22]. It has generally been found that initial imperfections tend to de-
crease the rigidity and ultimate strength of plates. The weld-induced residual stresses
have been shown to reduce the plates’ stiffness and strength [23]. Therefore, numerous
studies have investigated the influence of the initial imperfections, welding-induced res-
didual stresses, different loading, and boundary conditions on the plates’ structural re-
sponse.

Kmiecik [24] investigated the influence of the general initial imperfections formulated
by Fourier components, which were pioneering. The initial theoretical imperfections
had been assumed as the buckling mode in most cases. He concluded that the initial im-
perfection buckling mode component has a significant reducing effect, whereas the rest
have a stiffening influence. The impact of different modes of imperfections was also studied
in [25,26] using the finite element method. In this period, several authors dealt with
the behavior of plates using numerical methods, such as in [27–29], among others.

Carlsen and Czujko [30] discussed the specification of tolerances for post-welding
distortions of plates. They demonstrated that only the buckling mode component of the
Fourier series expansion of the distortion shape significantly influences the plate strength.
In contrast, other Fourier components only have a marginal strengthening effect, consoli-
dating the findings in [24].
Dow and Smith [31] studied the effects of the localized imperfections on the compressive strength of long rectangular plates, where they investigated several initial imperfection modes, including localized distortions. They showed that the initial imperfection leads to ultimate load capacity and stiffness reductions. They concluded that localized initial distortions are associated with less pre-collapse loss of stiffness and more rapid post-collapse unloading than equivalent periodic distortions. The magnitude of the localized distortions governs the plate collapse. It was also concluded that the Fourier distortion components corresponding to the initial elastic buckling mode will give a non-conservative representation of the initial shape if a localized initial distortion exists.

Ueda and Yao [32] investigated the influence of the complex initial defect modes on the elasto-plastic large deflection behavior and ultimate strength of rectangular plates under compression. They showed the importance of the initial imperfection. The magnitude and the components of the initial imperfection also significantly influence the plates’ ultimate load carrying capacity, which consolidates the study performed by Kmiecik [24].

Guedes Soares and Kmiecik [33] investigated the compressive strength of unstiffened plates under uniaxial compression, accounting for the initial distortions using the finite element solution. They concluded that the uncertainty in plate strength depends strongly on the plate slenderness. Its most significant values are in the intermediate slenderness range and decrease with stocky plates, which agrees with the earlier formulation presented in [34].

Sadovský et al. [35,36] studied the influence of initial defects on the collapse strength of thin rectangular plates in longitudinal compression by normalizing the initial defects by the energy measure instead of the amplitude. They concluded that comparing the effects of the theoretical and measured initial defects upon the collapse strength and the buckling mode proved to yield a very conservative lower bound when adopting the amplitude to thickness ratio to measure the imperfections. A reasonably close lower bound was obtained using the buckling mode to normalize the initial defects by the energy measure.

Sadovský et al. [37] proposed an approach to the numerical study of the influence of the initial defects considered a random field on the resistance of in-plane loaded plates. The study demonstrated that a more realistic treatment of the effects of imperfections on the plate strength might lead to significantly less conservative design loads. Given that the initial imperfections are random and their impact is difficult to predict from a limited description of their shape, Sadovský and Guedes Soares [38] proposed the use of a neural network model trained with results of finite element calculations to predict the capacity of plates with imperfections and managed to obtain good results. An enhanced method in predicting the structural behavior of thick steel plates by using a random field approach has been proposed in [39,40].

Cubells et al. [41] used the photogrammetric technique to measure plates’ real initial imperfection to assess the plates’ structural capacity. They demonstrated the difference in the structural response using the initial imperfect geometry as calculated by this technique and the one modelled by the Fourier model. They concluded that the asymmetries of the initial imperfection are significant and influence the maximum capacity of the structures. The photogrammetry technique was used earlier to measure the deformation of three-dimensional structures [42,43] and in close range to determine the detailed distortions induced by welding on plates.

2.3. Impact of Welding Induced Stress

The importance of the residual stresses in plate strength has motivated the interest in calculating residual welding stresses [44–46] and the associated temperature distributions [47,48]. In this field, significant developments have been made by using finite element analyses to assess the temperature fields and the residual stresses. Many studies have adopted the Goldak et al. [49] model for modelling the transient welding process and cal-
ibrating the model’s parameters to the welding conditions [50]. Others compared predictions with experimental results [51–57]. While the validation of the permanent defects induced by welding is efficiently conducted, the validation of the residual stresses is much more complicated and uncertain. Thus much fewer studies exist with this type of validation [58].

More complex cases have also been studied, including multi-pass welding [59] and the effect of the sequence in multiple welding [60]. Proper sequences are chosen to reduce the weld induced distortions, but restraining the plate during welding is another approach adopted and studied [61–65].

The initial imperfection and welding-induced residual stresses on the square plate load capacity were studied in [22]. They concluded that the influence of the welding-induced residual stresses on the plate buckling is significant. When the plate is thin, the welding-induced residual stresses have little effect on the ultimate strength. In contrast, they significantly influence the ultimate capacity of thick plates if local bending is present.

Ueda and Yao [66] presented the fundamental behavior of plates and stiffened plates subjected to welding imperfections. They concluded that welding-induced stresses reduce the plate in-plane rigidity and ultimate load carrying capacity. The reduction is more significant when the plate slenderness is about 1.8. Only one component of the initial imperfection is amplified when the load is above the buckling load for thin and long plates. They become stable as the load increases, and only the deflection of this component influences the ultimate strength. As for long thick plates, the most considerable curvature of the initial imperfection is a leading cause that initiates the spread of the plastic zone in the plate, resulting in the load carrying capacity reduction. The maximum curvature influences the ultimate load-carrying capacity reduction more than the maximum magnitude of the initial imperfection.

Paik and Sohn [67] studied the influence of welding-induced residual stresses on high-tensile plates. They concluded that longitudinal welding-induced stresses significantly impact thick plates in terms of their load carrying capacity. Transverse welding-induced stresses have a negligible effect on the ultimate load carrying capacity if the longitudinal compression is predominant. However, they have a significant influence on the post-collapse regime of the plates.

The shakeout effect on welding-induced residual stress for a plate under uniaxial cyclic load was investigated in [68], where it was demonstrated that it might lead to a 63.1% and 27.2% welding-induced residual stress reduction in the tensile and compressive stresses, respectively, when the applied cyclic load is 75% of the material yield strength, or cyclic load 2. When the applied cyclic load is 50% of yield stress, cyclic load 1 reduces the tensile stress by 40% and the compressive stress by 22.2%, demonstrating that the ships may gradually shake out the longitudinal welding-induced stresses.

Tekgoz et al. [69] studied the influence of welding-induced stresses with a moving heat source on the load carrying capacity of the plates, accounting for several plate thicknesses. They demonstrated that tension stresses are developed around the weld beads when the plates are welded in the middle. The angular plate distortions may increase the plate load carrying capacity in plates of a certain slenderness.

Gordes Soares and Kmiecik [70] proposed a methodology to evaluate the structural performance of rectangular plates accounting for the welding-induced stresses. Several strength influencing parameters were considered, and it was concluded that the welding-induced stresses influenced the plate pre-collapse significantly and the ultimate load capacity.

2.4. Load and Boundary Condition Impact

Gordes Soares and Kmiecik [71] investigated the influence of boundary conditions, accounting for initial imperfections, in square plate strength. They concluded that for stocky plates, the boundary conditions have an impact almost equivalent to those in per-
fect plates. However, when the initial imperfection is significant, their strength is insensitive to the boundary conditions. As for thin plates, it was concluded that the influence of initial imperfections is small, but the boundary conditions have significant effects.

A study about the influence of initial imperfections on a restrained plate was presented in [72]. It was demonstrated that restrained plates might have a larger ultimate capacity than the yield stress in stocky plates with small initial imperfection amplitude. Guedes Soares [8,10] had already considered this in a study where the design equations predicted an ultimate capacity larger than 1.0 in some conditions. It was concluded that high-order modes lead to minimum ultimate strength compared to the critical mode. A stress-induced direction perpendicular to the loading can reach very high values, generating non-negligible forces in the support structures.

The study of transverse strength is often related to analyzing the strength of plates in biaxial loading [73–75], and the compressive strength of rectangular plates under biaxial load and lateral pressure was studied in [76]. A method based on the formula used by the American Bureau Veritas or Det Norske Veritas for the plates having plate slenderness of more than 1.3 was suggested. The proposed method was extended to account for the initial defects and lateral pressure.

An investigation related to the transverse strength of the rectangular plates under transverse compression based on the test data collected and numerical results was performed in [77]. Several formulations have been compared and based on the results, and they proposed an alternative formula for the transverse strength of the plates. Alternative formulations have been discussed in [15,78,79], while numerical results are available in [75] and experimental results in [80].

Numerous authors have also studied the combined compressive loading and lateral pressure effects on the load capacity of plates [17,20,81–84].

A benchmark study was performed in [85,86] using several methods to estimate the limit state of unstiffened plates under bi-axial compressive load lateral pressure. It concluded that plate ultimate strength behavior is significantly affected by plate initial deflection shape, boundary conditions, and loading conditions. It was concluded that DNV-PULS [87] and ALPS/ULSAP [88] methods are beneficial for the ULS assessment of unstiffened plates in terms of the computational effort and the resulting accuracy, compared to more refined non-linear finite element solutions [89].

3. Stiffened Panels

In plate panels, longitudinal stiffeners provide the necessary support to the plates, ensuring that they retain the required strength [15]. A stiffened panel is an assembly of plate elements and support members, namely longitudinal stiffeners, and the interaction between the plate elements and support members regarding their geometrical and material properties. Other factors such as loading condition and initial imperfections play an essential role in the ultimate strength, buckling, and plastic collapse patterns of stiffened panels [90].

3.1. Failure Modes of Stiffened Panels

Failure of panels is usually classified as plate-induced failure, column-like failure, tripping of stiffeners and overall grillage failure [23,91]. However, a panel will be subjected to all failure modes, and it will finish up collapsing in the mode corresponding to its lowest strength [92]. It is common to calculate the strength of the weakest collapse pattern, representing the stiffened panel in question.

Plate-induced failure assumes that the stiffeners will carry the loads up to the material yield stress; therefore, they are fully effective throughout the external load exposure. In contrast, the plate itself induces failure, which may provide, in a sense, a higher bound of the strength. The effective plate width approach represents the reduction of plate stiff-
ness. When the maximum stress acting on the plate reaches the material yield stress, overall collapse occurs. The response of a short stiffened panel with a length approximately equal to the width of the plate between stiffeners is dominated by plate failure [23]. However, as pointed out in [15], the inability of the structure to carry an additional load will be limited either by panel collapse or by grillage instability in which the plate elements and stiffeners weaken together. Therefore, stiffened panel collapse is represented by the failure of the plate and stiffener together.

Additionally, ship panels are longer in the critical locations where the ship sustains higher load levels, in which plate-induced failure possibility is low, and grillage failure is normally avoided by ensuring that the transverse frames are of adequate size. They are stiff enough to stimulate inter-frame panel collapse. Several design formulas have been proposed to predict the load-shortening response of stiffened panels accounting for different collapse modes.

3.2. Collapse Strength Assessment

Design formulas for two primary failure modes—strut or column failure of the stiffened plate and tripping of the stiffeners for stiffened panels under compressive load—were proposed in [15]. The beam-column failure of stiffened plates is based on the formulation suggested by the Johnson-Ostenfeld beam-column approach, which accounts for the inelastic weakening effect of column buckling of the plates and struts that have very high elastic buckling stress where the buckling occurs in the elastic–plastic regime. The plate and stiffener are subjected to the same maximum stress load, and the plate effective width approach to account for the weakening effect when plates are in the post-buckling stage is also accounted for.

Carlsen [93] proposed another method based on the Perry-Robertson method, which assumes that when the maximum compressive stress at the outermost fiber of the column cross-section reaches the material yield stress, the collapse is considered to take place.

Guedes Soares and Gordo [92] demonstrated the performance of three methods for beam-column failure as proposed in [15,93,94], where stiffened panels are under in-plane uniaxial compressive load based on the comparison between the numerical and experimental results. They demonstrated that the effective width prediction for plate-induced failure proposed by the Faulkner method falls between the ABS, which has an optimistic prediction, and that of Carlsen, which has a conservative prediction as a function of plate slenderness.

Paik and Kim [95] pointed out that the stiffener-induced failure mode based on the Perry-Robertson formula generally provides overly pessimistic results. In contrast, the plate-induced failure mode based on the Perry-Robertson formula reasonably predicts the ultimate panel strength in a specific range of stiffener dimensions, following the beam-column-type collapse mode.

Paik and Thayamballi [96] proposed an empirical formula as a function of the column slenderness and the attached plate slenderness coefficients based on extensive experimental data to estimate the ultimate load carrying capacity of stiffened panels, which implicitly accounts for stiffener web buckling or tripping as well as the beam-column-type collapse. Several empirical formulas to predict the load carrying capacity of the stiffened panels were reported in [97–100].

Ozdemir et al. [101] proposed a new method to predict the ultimate load capacity of the stiffened panels using the large elastic and initial yield solution. The proposed model was shown to be good enough to predict the ultimate load capacity of the stiffened panels compared with finite element solutions.

However, the calculation of the prediction of the collapse strength of stiffened panels is not sufficient to adequately represent the collapse behavior of hull girders. Therefore, other authors proposed several methods to predict the load-shortening curves of a stiffened panel, accounting for the collapse mode of stiffened panels.
An approximate incremental method to estimate the load-shortening curves of stiffened panels, including post-collapse behavior accounting for the initial imperfection and welding-induced residual stresses based on the proposed model, has been reported in [7,15]. The estimated load-shortening curves were compared to those predicted by the finite element solution, demonstrating a good agreement.

In the study of Yao and Nikolov [91] and its follow-up, Yao and Nikolov [102] proposed a method to calculate the average stress-strain behavior of stiffened panels to estimate a hull girder’s ultimate load capacity. The method involves formulating the coupled flexural-torsional behavior of angle bar stiffeners, including stiffener tripping, which is one of the most critical stiffened panel failures since it comes with a very steep reduction of post-collapse strength and largely influences both the ultimate and post-collapse capacity of hull girders.

The International Association of Classification of Societies, IACS [103,104] has provided several collapse modes for evaluating the average stress-strain relationship of stiffened panels in a progressive collapse analysis based on the work in [7].

Li et al. [105] proposed an adaptable algorithm to predict stiffened panels’ complete load-shortening curve under uniaxial compressive load. It has been shown that the proposed model is practical and efficient and can be further incorporated in the definition of hull girder strength assessments.

3.3. Impact of Governing Factors

Numerous studies have been focused on the impact of factors governing the load carrying capacity of stiffened panels, namely the external loading conditions, initial imperfections, welding-induced residual stress, etc.

3.3.1. Impact of Load and Boundary Conditions

Byklum and Amdahl [106] presented a computational model to predict the local buckling and post-buckling of stiffened panels, accounting for biaxial in-plane compression or shear and lateral pressure. The method predictions have been compared with the finite element solution and found to be in good agreement.

A series of elastic-plastic analyses for continuous stiffened plates subjected to combined transverse thrust and lateral pressure were performed in [107]. They proposed a formula based on FEM to estimate the ultimate strength of continuous stiffened panels under combined transverse and lateral pressure. It was demonstrated that the proposed formula is in good agreement with the FEM.

A benchmark study of several methods used to estimate the limit state of stiffened plates under bi-axial compressive load and lateral pressure was performed in [86]. It was concluded that DNV-PULS (2006) and ALPS/ULSAP (2006) methods are beneficial for the ULS assessment of stiffened plates in terms of the computational effort and the resulting accuracy.

Xu et al. [108] investigated the influence of model geometry and boundary conditions on the ultimate strength of stiffened panels under uniaxial compressive loading. They concluded that the boundary condition influences the ultimate strength and the collapsed shape of the stiffened panels. The fundamental advantage of periodic symmetric boundary conditions is that they can deal with either the symmetric or asymmetric collapse deformation mode. However, symmetric boundary conditions can only represent symmetric deformation. The influence of the boundary conditions on the load capacity of the stiffened panel using the numerical solution and experimental tests have also been reported in [109].

Tanaka et al. [110] performed a series of collapse analyses on 720 stiffened panels to evaluate the ultimate strength of the stiffened panels under longitudinal thrust by varying the numbers, types, and sizes of stiffeners and aspect ratio and slenderness ratio of local panels partitioned by stiffeners. They presented several conclusions. When smaller stiffeners are attached to thicker panels, overall buckling dominates the collapse behavior. The
ultimate strength widely differs depending on the number of stiffeners and the aspect ratio of the whole stiffened panel. When larger stiffeners are provided, the collapse of local panels partitioned by the stiffeners dominates the collapse behavior. The ultimate strength of a stiffened panel under longitudinal thrust evaluated by CSR-B is in general lower compared to that assessed by FEM analysis.

Xu et al. [111] studied the ultimate load capacity of continuous stiffened panels under a combined longitudinal compressive load and lateral pressure using the analytical and finite element solutions. A two-span model with periodical boundary conditions was implemented. They demonstrated that with the increase of lateral pressure, the ultimate strength decreased with plate-induced failure, but it increased in the case of the stiffener-induced failure. The in-plane constraints on the longitudinal edges have a significant effect that enhances the load carrying capacity of the stiffened panels.

3.3.2. Impact of Material Properties and Welding Induced Effects

A study of the ultimate capacity of a stiffened panel accounting for different material and geometrical parameters was presented in [112]. Namely, material yield and ultimate tensile stress, Young’s modulus, and plate initial imperfection and plate column slenderness were defined using the Monte Carlo simulation. The influence of these parameters was demonstrated using the ANOVA (analysis of variance) methodology to investigate the impact of these parameters on the load carrying capacity. The ultimate load capacity was estimated using the finite element solution.

Compressive tests on the stiffened panels with intermediate slenderness were performed in [113]. They studied the performance of conventional and U-type stiffened panels with hybrid material properties. It was demonstrated that hybrid panels have better performance than full S690 (material with a high tensile yield stress of 690 MPa) panels. The S690 material increases the average ultimate strength in the order of two times or higher when compared to mild steel when used in the plating. Experimental tests were also performed on short and long continuous panels in [114] and on long and narrow stiffened panels in [115,116].

Tekgoz et al. [117] investigated the influence of welding-induced stresses on the load capacity of stiffened panels. Two methods, namely, those testing the idealized welding stress field and modified material stress-strain curves, were implemented to study the impact of residual stresses. They concluded that the modified stress-strain curve approach is a fast approach showing a good agreement with the idealized welding stress field approach in terms of load capacity assessment of stiffened panels.

Tekgoz et al. [118] studied the impact of the welding sequences on the load carrying capacity of a stiffened panel, where the welding is simulated with a moving heat source. It was demonstrated that the welding sequence is the parameter that most affects the lateral deformation of the stiffener, which leads to more load carrying capacity reduction. The welding sequence profoundly influences the plate edge buckling pattern.

Gannon et al. [119] studied the influence of welding-induced residual stress release by the linear elastic shakedown phenomenon and its impact on stiffened panels’ ultimate load carrying capacity. They demonstrated that the ultimate capacity might increase as much as 7%. They concluded that the ultimate load capacity increase depends on the failure location and the level of the welding-induced residual stresses.

Li et al. [120] investigated the influence of welding-induced residual stresses on the load capacity of stiffened panels using the finite element solution and the one provided by the standard structural rules. It was concluded that residual stress with average severity would reduce the ultimate load capacity significantly. The modified material’s stress-strain curves were adopted to incorporate the influence of welding-induced stresses. The modified stress-strain curve approach did not correlate well with the one predicted by the finite element solution, but they concluded that it may still be a practical approach.
4. Box Structures

Box structures are used for different problems because they may represent ship structures on more minor scales. Therefore, numerous box girder case studies have been performed to understand ships’ overall behavior using different structural and material configurations.

One of the first box girder studies oriented to represent hull girder was performed in [121], where the author performed collapse tests on seven box girders that were subjected to pure bending load. Ostapenko [122] proposed a method to determine the ultimate strength of the longitudinal hull girder under bending, shear, and torque. The method’s validity has been verified by performing three box girder collapse tests under the specified loadings.

Nishihara [123] proposed a simple method to estimate the ultimate hull girder capacity under a pure bending load. He performed several box girder tests to represent different ship structures, namely, bulk carrier tanker and container ships, to validate the proposed method.

A four-point bending test on a box girder to represent the mid-ship region of conventional ships or FPSOs was presented in [124]. The authors presented two methods to evaluate the level of the residual stresses indirectly from the experimental data. The initial cycles to release welding-induced stresses led to loading memory effects on the structure, influencing the moment-curvature relationship.

The experimental behavior of a mild steel box girder under a pure bending moment was investigated in [125]. Several insights were provided in this experiment, including that the column slenderness controls the type of collapse of the structure. In essence, high column slenderness leads to more collapse, followed by a massive discharge of load during failure of the structure. The proposed approximate method based on the progressive collapse of stiffened plate elements gives a reasonable estimation of the ultimate load supported by the structure. It allows reproducing the effect of residual stresses on the box behavior.

Tekgoz et al. [126] studied the effect of the initial imperfection and transverse net section shapes on the ultimate strength of ship-shaped structures subjected to asymmetrical bending loading. They demonstrated that a triangular net section performs better than a square one when subjected to a hogging bending load. The net sectional sensitivity analysis demonstrated that a minimum ultimate bending moment is achieved at a different heeling angle to that of the other net sectional shapes. They also proposed a method to predict the continuous neutral axis rotation during an incremental load, which agrees with the one predicted by the finite element solution.

5. Ship Hull Structures

Ship structural collapse, or longitudinal strength, assessment has been a study of interest for a long time to ensure that ships withstand external loads without failure and provide safety for crews and traded cargoes throughout their lifetimes.

The prevention of hull collapse is the most critical task in ship structure design and safety assessment. When the strength of ship structures is assessed, it has been common to consider three strengths: longitudinal, transverse, and local strength. Among these, longitudinal strength, which is the hull girder strength against longitudinal bending, is the most fundamental and important strength to ensure the safety of ships [127]. Thus, an accurate and efficient method for computing the ultimate hull girder strength is always required in robust ship structural design [90].

Several examples of ship failure have led to catastrophic damage to the environment and loss of human life and the traded cargo. One of the most well-known is the structural collapse of the Titanic and subsequently the loss of thousands of human lives in 1912. A single-hull oil tanker, the Energy Concentration, broke in two during the unloading of its cargo in 1980. The single-hulled oil tanker Erika broke in two in rough weather in 1999; it
was thought the sea weather was so severe that she could not withstand the external load. Reasons for these incidents include poor execution of cargo loading/unloading operations, age-related degradations, and unexpected events.

5.1. Ultimate Strength Assessment

The first known shipload capacity assessment dates from the 1850s when Isambard Kingdom Brunel designed the Great Eastern, built of iron. He applied the beam theory to estimate the bending stress acting on the ship where the failure concept was breakage of the iron plates in the deck and bottom under tension load. In 1874, John calculated the acting bending stresses assuming the wavelength equals the ship’s length using the beam theory. However, it was observed that the beam theory underestimated the actual strain/displacement during a real ship collapse, that of the Wolf, which was attributed to the weakening effect of local buckling and the impact of shear lag [127]. These effects are neglected in the beam theory since it assumes a uniform stress distribution across the compressed flange.

Several actual or small-scaled ships were subsequently built to perform collapse tests to understand the ships’ vertical bending collapse behavior [128–134]. These collapse experiments had similar findings in that they found the compressed flange of the ships led to buckling/plastic collapse, which consolidates the point that a full plastic bending moment is not attained due to the buckling phenomenon. It is an essential issue in the structural strength assessment of hull girders. The torsional strength of hull girders has also been experimentally documented in [135,136].

Yao [137] presented a review of hull girder collapse strength in which several advanced and straightforward methods were investigated in terms of their hull collapse prediction accuracy, namely simple techniques such as initial yielding, assumed stress distribution, and advanced methods such as progressive collapse methods with idealized or computed stress-strain curves, ISUM, and the finite element solution, FEM. It was concluded that only the advanced methods could capture the progressive collapse behavior of hull girders.

The initial yield assumption to estimate hull collapse strength is not an accurate indicator of the actual hull capacity given the fact that in real ship collapse, it involves geometrical non-linearity, being the panel buckling, and the material non-linearity, being the material plasticity factors that need considering of the evaluation of the hull collapse. It requires a progressive approach from the initial to the final collapse stage, which includes interacting with the hull girder’s elements. Each element’s strength contributes to the overall hull strength. Therefore, ship structural capacity assessment has moved into a more sophisticated phase, which involves the geometrical and material non-linearity of the structures; that is, the ultimate strength or ultimate limit state criteria.

Caldwell [138] pioneered the ship longitudinal ultimate capacity assessment that accounts for the weakening effect of the buckling phenomenon in the compressed flange of the hull girder by reducing the material yield stress. He assumed a bending stress distribution over the ship cross-section at the ultimate stage; then, the fully plastic vertical bending moment was calculated. The elements under tension are yielded, and those under compression reach their ultimate individual capacity, accounting for the buckling phenomenon. However, in this method, the transition from the linear stage to the fully plastic stage is neglected without considering the time lag between the components in terms of their failure. This assumption is not possible because of the weakening effect of the buckling phenomenon. However, the stress distribution presumed by Caldwell does not represent the ultimate limit states of modern ship structures, resulting in overestimated calculations of the ultimate hull girder strength [90].

Ueda and Rased [139] proposed an idealized unit method (ISUM) to estimate the ultimate transverse capacity of ship structures. The new ISUM elements were developed and reported in [140,141].
Smith [142] proposed a progressive collapse method, also widely used as the Common Structural Rules (IACS, 2015), to estimate the longitudinal strength under pure bending load. The ship cross-section is divided into components defined as plates with associated stiffeners, hard corners, or plate elements. The average stress and average strain relationships of the elements are firstly calculated, accounting for the plasticity and buckling. The average stress-strain curves later are used in the progressive collapse analysis, assuming that the load is path-dependent and incrementally increased in the form of curvature. More details on the progressive collapse procedure based on Smith’s method have been reported in [143].

In this method, two main assumptions are made. Firstly, the ship cross-section remains on a plane throughout the external load exposure. Each element is independent and progressively loses its strength and stiffness during the incremental permissible curvature, which includes the time lag of the component failure enabling the collapse to be progressive.

The first assumption rules out the possible influence of the vertically acting shear force that may induce cross-sectional warping deformations. The linear strain distribution over the hull girder cross-section needs to be updated at each curvature increment, accounting for the additional warping strains. It also rules out the influence of the shear on the components buckling and material yield strength definition, meaning the shear’s impact on the individual component buckling strength needs to be accounted for with an updated material yield definition. It is a fact that probable ship failure occurs where the maximum bending moment takes place, and shear forces are negligible. However, the importance of the time-dependent load combination, shear, and bending forces should not be neglected.

The second assumption neglects the possible influence of the elements on each other as far as their stress-strain response is concerned, and the non-uniform external bending load that the ship side shell elements are subjected to during the vertical bending moment, which leads to both the compression and in-plane bending load that influences the side shell buckling strength. The Smith method prediction is profoundly affected by the accuracy of the individual component stress-strain curves.

For example, Rigo et al. [144] performed a sensitivity analysis of an ultimate hull girder bending moment using the Smith method. They studied the influence of three influencing factors in the progressive collapse analysis, PCA, namely decomposition of the hull cross-section into the elements, the meshed model, evaluation of the average stress-strain relationship, and execution of the progressive collapse analysis. They demonstrated that the assessment of the ultimate strength of individual elements is the most influencing factor and the average stress-strain relationship of the individual elements is not negligible. Several conclusions were presented; for example, a PCA model is better than another if the mesh model of the structure is less simplified.

The International Association of Classification of Societies, IACS [103,104] has initiated the calculation of the ultimate load carrying capacity of hull girders. Several collapse modes for evaluating the average stress-strain relationship of stiffened panels have been presented to be used in the progressive collapse analysis, as initially proposed in [142]. The progressive collapse method has also been documented in several benchmark studies [1,145,146].

Paik and Mansour [147] proposed a simple analytical formula by assuming a credible bending stress distribution over the hull cross-section at the collapse stage to predict the ultimate load capacity of hull girders under a vertical bending moment involving single and double hull ships. However, the method assumes a uniform stress distribution along the flange under compression. The experimental ultimate load capacities of several box girders and small-scale ships were presented. The ultimate experimental capacities were compared with the proposed method and several existing analytical and empirical formulations [148–152]. There are significant differences observed in the ultimate moment results from these formulas used in the comparison. They concluded that the proposed
method is in good agreement with the experimental and numerical predictions and may be helpful in preliminary design estimates of the ultimate strength of ships under a vertical bending moment.

5.2. Buckling and Lateral Pressure Impact on Collapse Strength

Several authors have implemented Smith’s method over the years. Yao and Nikolov [91,102] implemented the Smith approach to predict the load carrying capacity of several box girders and ship structures. They proposed an analytical solution to calculate the plate and stiffened panel stress-strain curves to be used in the progressive collapse analysis. It was shown that the cross-section could not carry the full plastic bending moment due to the local buckling in the compression side of bending. More decrease was observed in ultimate strength under sagging conditions than hogging conditions. It was demonstrated that the tripping of the stiffened panels leads to a 5% ultimate capacity decrease. They concluded that the presented method deals with only one cross-section. It can be improved by incorporating the loads acting in transverse directions and the vertical and horizontal shear forces.

Gordo and Guedes Soares [153] proposed an approximate method using the Smith method to evaluate the hull girder collapse strength under pure bending load. They presented several box girder collapse tests and 1/3-scaled frigate ship collapse results and compared the accuracy of the approximate method.

Yao et al. [154] investigated the influence of lateral load pressure on the ultimate load carrying capacity of a ship’s hull girder under a longitudinal vertical bending moment. The proposed method to estimate the average stress-strain relationships of the plate and stiffened panels to be used in the progressive collapse analysis was compared with the one predicted by the finite element solution accounting for the lateral pressure where some discrepancy was observed, citing the assumption of the plastic formations. It was demonstrated that in the studied ship case, MV Energy Concentration, the lateral pressure effect on the load carrying capacity was not significant.

Garbatov et al. [155] presented an approach to verify the hull girder ultimate bending moment capacity of a real structure according to the Class Society Rules based on experimental results scaled by the dimensional theory. For this purpose, three experimentally tested box girders were used to verify the applicability of the presented approach. They demonstrated that the possible deviation of the correct estimation from the predicted one, for the analyzed real and model structural configurations, in the worst case, may be underestimated by 8.3% in the present example. They concluded that the proposed method might validate the ultimate global strength of real ship hull structures, in the phase of the new structural design or during the service life, and calibrate the newly developed codes.

The finite element solution is commonly used for the ultimate collapse analysis of marine structures, initially performed in [156]. Several studies have been conducted to predict a hull girder’s load carrying capacity, accounting for pure bending or combined loading conditions and the lateral pressure using the finite element solution, as documented in [157–166].

6. Conclusions

A review of advances in the ultimate strength assessment of intact ship hull structures has been provided, showing that the structural behavior of steel plates, stiffened panels, ship-shaped box girders, and ship hulls had been extensively studied under different loading and environmental conditions.

It is concluded that there is still room for further studies on the impact of manufacturing and environmental conditions during ship service on the collapse modes of plates and stiffened panels.

Possible analytical solutions to estimate the average stress–strain relationship of plates and stiffened panels under monotonic and cyclic loads and the influence of the acting shear on the collapse strength of hull girders are also worth investigating.
Additional attention should be paid to the ultimate strength assessment of ship structures in service, which are typically subjected to very severe environmental conditions; these add to initial manufactory imperfections, and more imperfections are induced related to corrosion degradation, crack growth, collision, etc. [167].

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