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ESTIMATION OF BUCKLING RESPONSE OF THE DECK PANEL IN AXIAL COMPRESSION

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ABSTRACT

In this work, buckling strength assessment of a deck of a double hull oil tanker is carried out using the non-linear finite element code ADVANCE ABAQUS. The comparisons are performed with the Det Norske Veritas (DNV-GL) PULS (Panel Ultimate Limit State) buckling code for the stiffened panels, DNV-GL Classification Notes (CN) No.30.1 and the DNV-GL Ship Rules.
The case studied corresponds to axial compression. Two levels of imperfection tolerances are analyzed, in accordance with the specifications in the DNV-GL Instruction to Surveyors (IS) and the DNV-GL Classification Notes No. 30.1. Both "as built" and DNV–GL Rule "net" dimensions are analyzed.
The strength values from ADVANCE ABAQUS and PULS are very close. DNV-GL CN 30.1 is in conservative side, but the strength differences between the "as built" and "net" dimension cases are consistent with the finite element analysis results.
This paper gives a brief description of the background for the stiffened panel models used in PULS, and comparison against non-linear FE analysis, and DNV-GL Classification Society Rules. The finite element code ADVANCE ABAQUS is employed in a non-linear buckling analysis of a stiffened deck panel on a double skin tanker that is subjected to a Condition Assessment Program (CAP) hull survey. The aim of the analyses has been to validate and compare the buckling capacity estimates obtained from PULS, DNV-GL Classification Notes No.30.1 (CN 30.1) and the DNV-GL Ship Rules.

Keywords: buckling failure; non-linear finite element analysis; deck panel; initial imperfection; collapse mechanism

INTRODUCTION

Ship and offshore structures are basically an assembly of plate elements and estimation load-carrying capacity or the ultimate strength is one of the most important criterion for estimated safety assessment and rational design on the ship structure. In addition, structural elements making up ship-plated structures do not work individually under external load. One of the critical collapse events of a ship structure is the occurrence of overall buckling and plastic collapse of deck structure subjected to longitudinal bending. Hence, the deck plates are reinforced by a number of longitudinal stiffeners to increase their strength and load-carrying capacity. For a rational design avoiding such a sudden collapse, it is very important to know the buckling response and collapse pattern of the stiffened plate subjected to axial compression.

Stiffened panels' structural response under compressive loading is a topic of significant practical interest in ship design. This applies for the detail design phase as well as for ships in the service phase for which a trustworthy strength and safety margin assessment are of paramount importance. It is well known that post buckling and ultimate strength limits only can be treated in a consistent manner using non-linear plate theory. This fact has for many decades been an obstacle for practising engineers and designers since resort to advanced and time consuming non-linear finite element programs and expert judgements were a prerequisite for assessing the strength of critical elements. However, with the recent development of computers, it has become feasible to make use of buckling models based on non-linear plate theory. By introducing semi-analytical computerized ultimate strength models into ship and offshore rules and standards, engineers and designers will improve their understanding of non-linear structural response. The result will be more optimal and robust design solutions with more effective use of the material and improved control of the actual safety margins against failure. Corrosion margins and minimum thickness requirements for ships in service can be prescribed with larger confidence than hitherto possible with simpler and more traditional curve fitting methods.

Ko et al. [1] performed a series of FEM elastoplastic large deflection analyses on a stiffened plate with flat-bar, angle-bar and tee-bar stiffeners to examine numerically characteristics of buckling and ultimate strength behavior according to the analysis method of ship's stiffened plate subject to axial loading.

Ozguc et al. [2] developed the new simple design equations for predicting the ultimate compressive strength of stiffened plates with initial imperfections in the form of welding-induced residual stresses and geometric deflections were developed in the study. To perform ANSYS elastic-plastic buckling analyses, a non-linear finite element method was employed, where a wide range of typical ship panel geometries such as 60 different models was accounted for. Reduction factors of the ultimate strength were produced from the results of 60 ANSYS inelastic finite element analyses. The accuracy of the proposed equations was validated by the experimental results. Comparisons indicated that the adopted method had sufficient accuracy for practical applications in ship design.

Paik et al. [3] concentrated on methods for the ultimate limit state assessment of stiffened plate structures under combined biaxial compression and lateral pressure actions considering the bottom part of an AFRAMAX-class hypothetical double-hull oil tanker structure. Three methods, namely ANSYS nonlinear finite element method, DNV-GL PULS method, and ALPS/ULSAP method were used.

Chaithanya et al. [4] evaluated the behavior of stiffened plates with different distortion levels in order to address a rational structural design procedure, as pre-existing and fabrication-related initial geometrical distortion from a structural design point of view. Non-linear finite element (FE) analysis using ABAQUS was carried out under axial loading condition to predict the behaviour and the buckling strength.

Xu and Soares [5] simulated numerically the behaviour of stiffened panels under uniaxial compression until collapse and beyond, and then compared with tests made to investigate the influence of the stiffener's geometry and the boundary conditions. The stiffened panel models have three longitudinal bays to produce reasonable boundary conditions in the longitudinal direction. The material and geometric nonlinearities were accounted for in the FE analyses. The initial geometric imperfections, which affect significantly the collapse behaviour of stiffened panels, were assumed to have the shape of the linear buckling mode. Four types of stiffeners were made of mild or high tensile steel for bar stiffeners and mild steel for 'L' and 'U' stiffeners to investigate different material and geometry configurations, and four boundary conditions were analyzed.

Tekgoz et al. [6] analyzed the effect of different finite element models on the ultimate strength assessment of stiffened plates, where the effect of element size, and type, boundary conditions, shape of initial imperfecation, thickness and net sectional configurations were accounted for. Four different finite element models and different structural configurations were compared to the solution described by the Common Structural Rules (CSR).

Cho et al. [7] proposed ultimate strength formulation for stiffened plates. The formulation was developed by a regression study using the parametric study results. The accuracy and reliability of the proposed formulation were compared with those of commercial packages, such as ABAQUS and DNV-GL PULS, and experimental results.

Zhang [8] presented a review and study on ultimate strength analysis methods for steel plates and stiffened panels in axial compression. Buckling and collapsing mechanisms of steel plates and stiffened panels were described. A study and further validation on the authors developed formula for ultimate strength of stiffened panels using a comprehensive non-linear finite element analysis, 110 models in total, and a wide range of model test results, 70 models in total, were carried out. Finally, applications of the developed formula to existing oil tankers and bulk carriers were presented.

Zhang et al. [9] investigated pitting corrosion effect on the ultimate strength of hull structural stiffened plates under uniaxial compression. In the dedicated analyses, the relative parameters such as sizes of panels, size and shape of pits, initial imperfections, boundary condition, and number of stiffeners were accounted for. The ultimate strength reduction formula of pitted stiffened plates based on corroded volume loss were obtained by the data analysis from lots of non-linear finite element analyses.

Ozdemir et al. [10] proposed a new approximate method based on analytical formulas to estimate the ultimate strength of stiffened panels, where a series of detailed elastoplastic large deflection FEA was carried out. The initial deflections were accounted for in the form of thin-horse mode plus overall buckling mode for the plates, and flexural buckling mode plus tripping mode for the stiffeners. A good agreement was obtained within all collapse scenarios studied.

Shi et al. [11] investigated the collapse mechanics of pitted stiffened plates using numerical approach and compared with the tests. A series of FEAs were performed to address the influence of pit damage. Pits can eventually induce the buckling and reduction of the ultimate strength capacity of stiffened panel. A formula was introduced with regards to the reduction of the plate slenderness ratio and column slenderness induced by pits.

In this study, buckling strength assessment of a deck of a double hull oil tanker is carried out using the non-linear finite element code ADVANCE ABAQUS [12, 13]. The comparisons are being performed with the DNV-GL

PULS [14] buckling code for stiffened panels, DNV-GL Classification Notes No.30.1 [15] and the DNV-GL Ship Rules [16]. The results and insights developed from the present study are summarized in terms of ultimate strength characteristics of deck stiffened plate structures.

THE MODEL FOR ANALYSIS

A Condition Assessment Program (CAP) strength check of a double hull oil tanker revealed a potential buckling strength problem in its deck structure. The DNV-GL Ship Rules, the DNV-GL Classification Notes No. 30.1 (CN 30.1) and the PULS buckling acceptance criteria indicated insufficient buckling strength.

The PULS buckling code is developed by DNV-GL for direct computational assessment of buckling limits and ultimate strength limits of stiffened panels based on non-linear large deflection plate theory. The idea is to combine a user friendly and easy to understand user interface, with advanced but still efficient direct calculations. The numerical algorithms included in the buckling code provide results for a given case in the order of a second on a standard modern personal computer [14, 18].

In principle, the PULS buckling models can be classified as semianalytical in the sense that they are based on the recognized plate theory of Marguerre [17] in combination with numerical techniques for solution of the governing equations. Using non-linear plate theory, second order membrane strains are accounted for, and the postbuckling response may be traced. The principle of minimum potential energy is used, together with Fourier series expansion of the displacements. The non-linear elastic equilibrium equations are solved, and the load-deflection path traced, using the perturbation technique in an incremental scheme with arc length control. Using arc length incrementation, complex response histories may be solved, including snap-through problems [18].

The deck structure is without intermediate longitudinal girders between the two longitudinal bulkheads, and has flat-bar stiffeners. Previous experience indicates that the acceptance criteria tend to underestimate the ultimate strength of this type of panel. On the other hand, the higher strength has been associated with a violently unstable collapse. A more accurate analysis of the deck panels was judged interesting both as a verification of the simplified buckling strength formulations as well as providing decision support in the CAP rating. A non-linear finite element buckling analysis of the deck panel using the ADVANCE ABAQUS program has therefore been undertaken.

The deck panel has been analyzed for both gross ("as built") and DNV-GL Ship Rule net scantlings (t-t_k) [16]. The dimensions for these two cases are given below Table 1 and Table 2 (measured between girders).

Tab. 1. Gross scantling for studied deck panel

Stiffener length	3770 mm
Stiffener spacing	735 mm
Number of stiffeners	13
Plate thickness	13.5 mm
Stiffener height	283 mm
Web thickness	18 mm
Profile type	Flat bar

Tab. 2. Net scantling for studied deck panel

Stiffener length	3770 mm
Stiffener spacing	735 mm
Number of stiffeners	13
Plate thickness	11.5 mm
Stiffener height	283 mm
Web thickness	15 mm
Profile type	Flat bar

It is noted that the panel is loaded in purely axial compression.

FINITE ELEMENT MODEL (FEM)

The high number of stiffeners justifies the use of a single stiffener (column) model to analyse this case. If this at all has any impact on the strength, this will be to the conservative side.

To reduce the uncertainties introduced through boundary conditions the finite element model extends over three frame spaces (1/2+1+1+1/2). The model is illustrated in Fig.1. It has six elements between stiffeners, twenty-eight elements between transverse frames and three elements across the stiffener height.

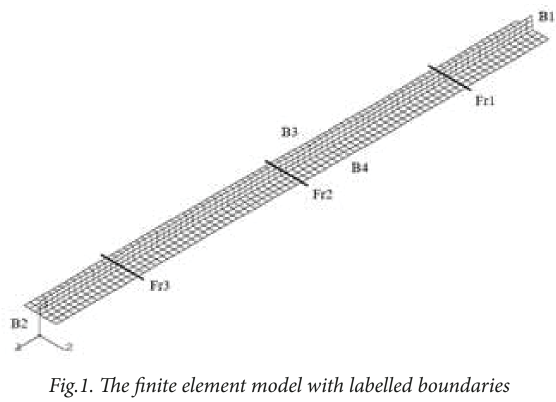

Fig.1. The finite element model with labelled boundaries

Strain hardening effect together with a bi-linear strain-stress curve as shown in Fig.2. The Cowper-Symonds rate enhancement formula is used to consider the effect of strain rate on material properties as given Eq.3, Eq.4 and Eq.5 that are shown in Fig.2. and Fig.3. The material parameters are shown in Table 3.

Tab. 3. The material properties

Young's modulus, E [N/mm²]	206 000
Poisson ratio, ν	0.30
Material yield stress [N/mm²]	235
Strain hardening parameter, ET [N/mm²]	1000
Strain rate (C)	40.4
Strain rate (P)	5.0

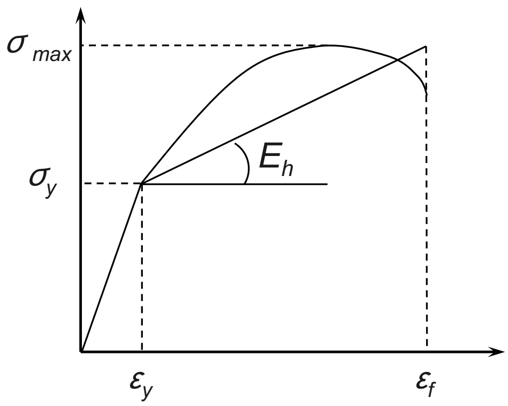

Fig.2. Stress-strain curve for bi-linear material

$$\sigma_p = \sigma_y + \frac{EE_h}{E - E_h}\varepsilon_p \quad (3)$$

$$E_h = \frac{\sigma_{\max} - \sigma_y}{\varepsilon_f - \varepsilon_y} \quad (4)$$

σ_y = Yield stress
E_h = Hardening modulus
σ_p, ε_p = Plastic stress & Plastic strain
E = Young's modulus

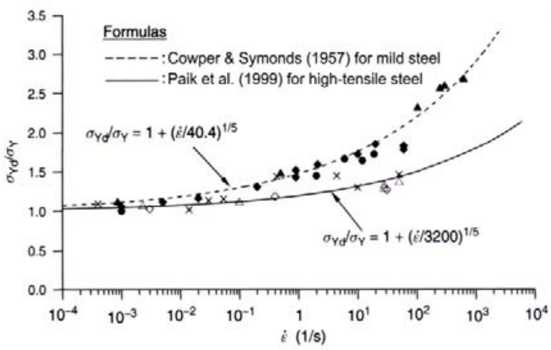

Fig.3. Strain rate effect

$$\frac{\sigma_{yd}}{\sigma_y} = 1 + \left\{\frac{\varepsilon}{D}\right\}^{1/q} \quad (5)$$

It is noted that for mild steel grade D = 40.4 and q = 5 are used.

Boundary conditions are imposed on the edges and lines indicated in Fig.1.

T [1, 2, 3] indicate translation constraints and on R [1, 2, 3] indicate rotational constraints about the 1, 2 and 3 coordinates as shown in Fig.1. Boundary conditions are imposed on the edges and lines indicated in Fig.1. In other words, free meaning no constraint and fix meaning is fully constrained.

- Symmetry conditions are given on edges B1 and B2. Namely, T [fix, free, free] and R [free, fix, fix].

This might represent a constraint on the deformation of the plate and on the web and flange of the stiffener, but the experience from other similar analyses [9, 10] indicates that this has small impact on the results. Edge B2 is fixed in the 1-direction.

- On edges B3 and B4 the rotation about the 2-axis is fixed (symmetry). Namely, T [free, fix, free] and R [fix, free, fix].

Edge B4 is fixed in the 2-direction, while edge B3 is free to translate in this direction but the edge constrained to remaining straight.

Lines labelled Fr1, Fr2 and Fr3 correspond to the positions of transverse frame. At these locations, the panel is fixed in the lateral direction. Furthermore, the stiffener is constrained to remain vertical in order to simulate presence of frames.

INITIAL IMPERFECTIONS

Imperfections in a buckling strength context usually refer to geometric imperfections (plate out-of-flatness, stiffener out-of-straightness, misalignments) and residual stresses. Both are a result of welding or plastic forming during manufacture. The presence of residual stresses has been disregarded in this study.

Two levels of tolerances on the geometric imperfections have been analysed, consistent with the specifications in the DNV-GL Instruction to Surveyors [19] (DNV-GL IS) and DNV-GL Classification Notes No.30.1. The relevant values of plate out-of-flatness and stiffener out-of-straightness specified in these documents are given in Table 4.

Tab. 4. Tolerances on plate out-of-flatness and stiffener out-of-straightness specified in the DNV-GL IS and in CN 30.1. See Fig.4 for a definition of the imperfection parameters.

	DNV IS	CN 30.1
δ_{P0} = 0.01s	0.01s (7.35mm)	6mm
δ_{S0} = 0.0015L	0.0015L (5.655mm)	13mm
δ_{T0} = 0.0015L	0.0015L (5.655mm)	13mm

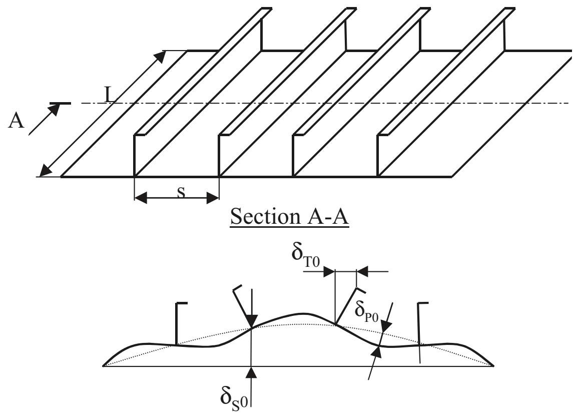

Fig.4. The imperfection parameters used in this study

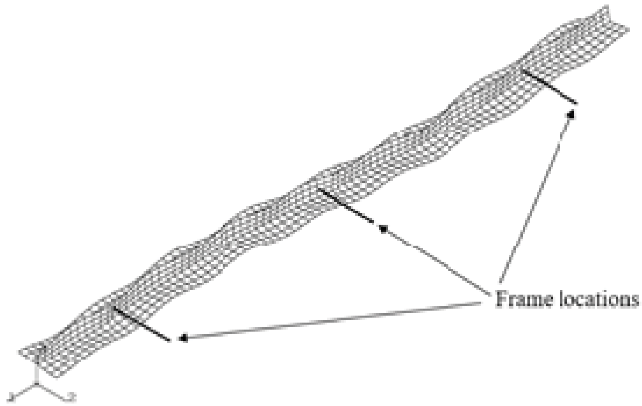

Fig. 5. Illustration of the imperfection shape used in the analyses

The shape of the imperfections is generally composed of a local component (plate out of flatness and stiffener flange out of straightness) and a global component (stiffener out of straightness) as shown in Fig.4. The local component is itself composed from a subset of the elastic buckling modes for the panel for the specific load combination at hand. In this case, a weighed combination of the ten first buckling modes is used. This procedure requires that the deformation pattern in the buckling modes exclude lateral deflection of the stiffeners, a requirement that is met in this case. Global stiffener imperfections are specified in a half sine wave pattern along the stiffener length, and with a constant value across the column cross-section. A magnified illustration of the resulting imperfection shape is shown in Fig.5.

LOAD APPLICATION

All analyses are being performed in displacement control, i.e. the non-linear solution is found by incrementing the magnitude of a specified edge displacement. This approach is selected because it eliminates that the need to apply the modified Riks algorithm [12, 13] in the solution. The Riks method is generally used to predict unstable, geometrically nonlinear collapse of a structure that can include nonlinear materials and boundary conditions. It often follows an eigenvalue buckling analysis to provide complete information about a structure's collapse; and can be used to speed convergence of ill-conditioned or snap-through problems that do not exhibit instability.

The Riks algorithm failed for some of the cases, by "backtracking" along the elastic unloading equilibrium path. Displacement control and load control are equivalent for axial load cases.

FINITE ELEMENT ANALYSIS RESULTS

The results from the finite element analysis will firstly be presented as equilibrium curves in a diagram spanned by a scaled nominal strain on the first axis ($\varepsilon/\varepsilon_F$) and a scaled nominal stress (σ/σ_F) on the second axis, where σ_F is defined as material yield strength and ε_F is yield strain. This will illustrate both the ultimate strength of the panel and its pre- and post-buckling response. The finite element results are being compared with PULS, CN30.1 and the DNV-GL Ship Rules.

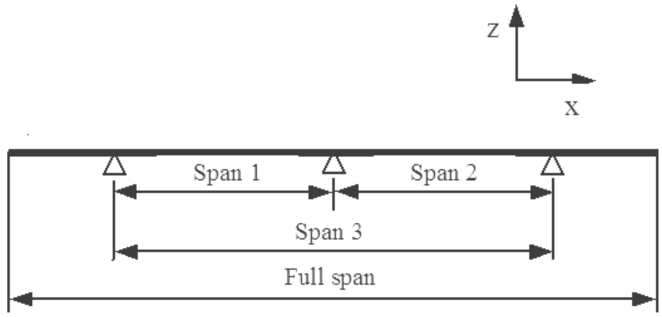

Fig. 6. Identification of the four mechanical systems selected for response visualisation

For a multi-span model, the load-displacement response will depend on what part of the system one considers. To illustrate this difference, the load displacement response is presented in Figs. 7-10 for the four mechanical systems identified in Fig.6.

Collapse of the panel is in all cases initiated and progresses in "Span 1" of the model, in the form of stiffener tripping close to the centre of the span. The tripping in turn reduces the out of–plane bending stiffness of the panel, leading to failure in lateral buckling.

Figs.7 and 12 illustrates the collapse modes for the DNV-GL IS Gross and the CN 30.1 Gross cases respectively. The two cases based on net dimensions show similar collapse modes as their gross dimension counterparts. Observe that the tripping failure differs in the two cases, an effect that most likely is the reason for difference in response between the cases based on the CN 30.1 imperfection tolerance level and the DNV-GL IS imperfection tolerance level. No attempt is performed to explain this difference in tripping behaviour, but it is noted that the difference must be related to the magnitude of the imperfections. In particular, it is the magnitude of the global stiffener imperfection that constitutes the difference between the models.

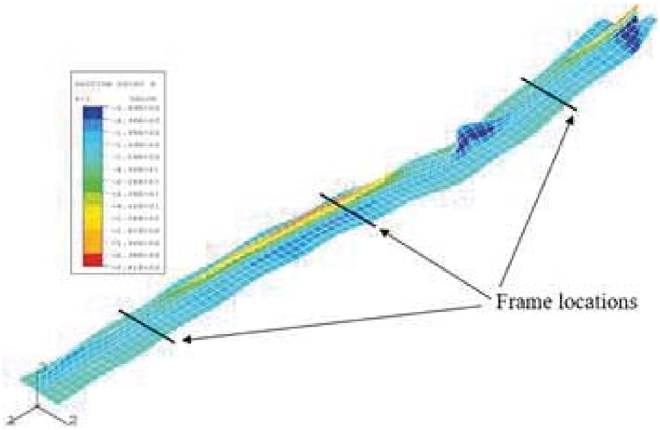

Fig. 7. Axial stress and displacement plot for the "DNV IS Gross" case. Note that displacements are magnified by five times

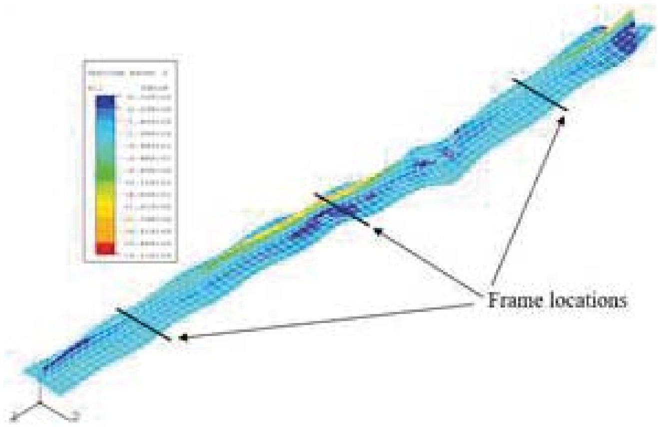

Fig.8. Axial stress and displacement plot for the "CN 30.1 Gross" case. Note that displacements are magnified by five times

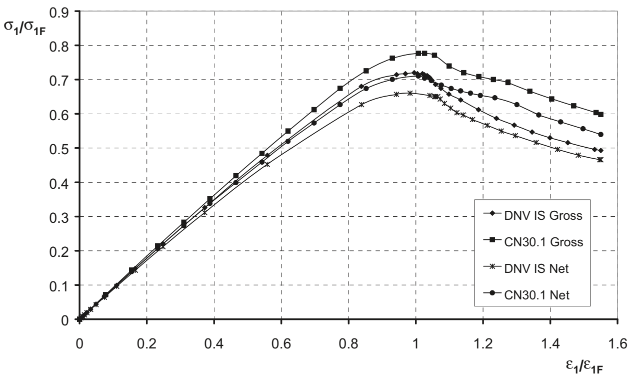

Fig. 9. Axial load vs. axial displacement response for the full model system

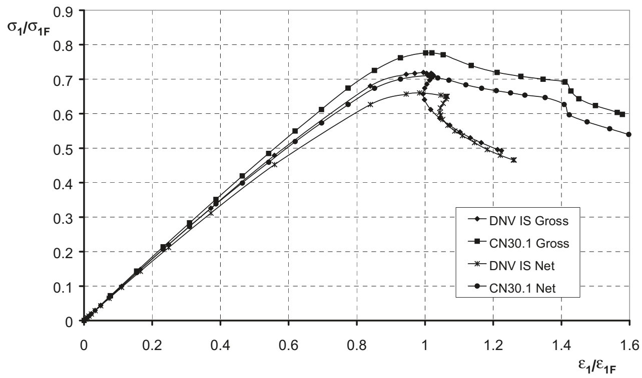

Fig. 10. Axial load vs. axial displacement response for the "Span 3" system

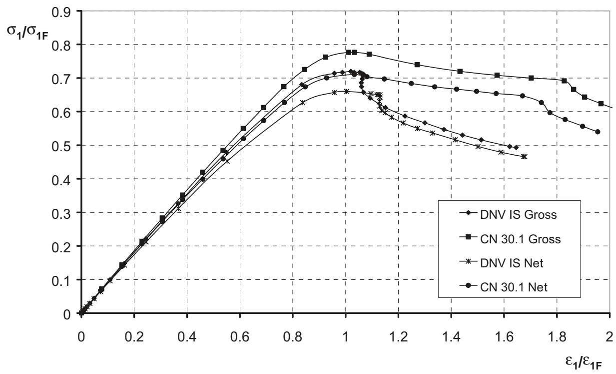

Fig. 11. Axial load vs. axial displacement response for the "Span 1" system

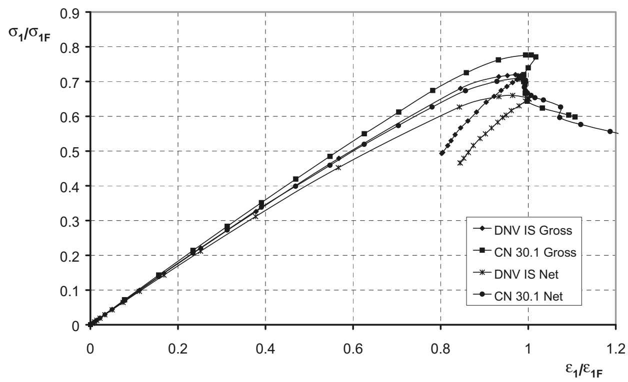

Fig. 12. Axial load vs. axial displacement response for the "Span 2" system

In "Span 2", the two analyse based on the DNV-GL IS imperfection tolerance level show an extreme "snap back" behaviour, whereas the remaining two cases show a smoother response. The response indicates that "Span 2" is unloading mainly elastically for the two cases based on DNV-GL IS tolerances. In the two cases based on CN 30.1 tolerances, a failure mode seems to be developing in "Span 2" allowing for an increase in axial displacement despite the decrease in load.

Clearly, the response of the full model is smoother than the response of the individual spans. This happens because a localised plate buckling deformation progresses at one of the panel ends, thus compensating for the decreasing displacement in "Span 2".

COMPARISON WITH SIMPLIFIED CALCULATION METHODS

None that the simplified strength formulations allow for a specification of an imperfection tolerance level. Strictly speaking, the DNV-GL Ship Rule and the PULS results should therefore be compared to the ADVANCE ABAQUS results relevant for DNV IS tolerance level, whereas the CN 30.1 results should be compared to the ADVANCE ABAQUS results relevant for the tolerance level specified in CN 30.1. On the other hand, the uncertainties related to the magnitude of the geometric imperfections is large, and there is no evidence that the imperfections are larger in ship than in offshore structures. An alternative approach is to interpret the results based on the CN 30.1 tolerance level and the DNV-GL IS tolerance level as lower and upper bound strength values, respectively, valid for typical stiffened panels in ship and offshore structures.

A summary of the strength values obtained from ADVANCE ABAQUS and the three simplified buckling strength formulations are provided in Tab.5. Clearly, the PULS strength results is in excellent agreement with the ADVANCE ABAQUS results based on the DNV-GL IS tolerance level. CN 30.1 appears to be conservative, in particular in comparison to the ADVANCE results relevant for the CN 30.1 imperfection tolerance level.

The DNV-GL Ship Rule strength estimate are higher than both the PULS and the CN 30.1 strength estimates, but still below the ADVANCE ABAQUS results relevant for the CN 30.1 tolerance level. Relative to the ADVANCE ABAQUS results, the Ship Rule strength estimates are higher for the gross dimensions than the net dimensions indicating that the Ship Rules do not exhibit the same qualitative trend as the ADVANCE ABAQUS analyses. Some lack of physical consistency must be anticipated since the DNV-GL Ship Rule strength estimates are governed by the plate-buckling criterion, whereas the collapse is governed by stiffener tripping. Both PULS and CN 30.1 indicate stiffener-induced failure mode.

Tab. 5 Comparison of panel buckling strengths for different analysis methods.

Analysis Id.	Buckling strength in gross dimensions [MPa]	Buckling strength in net dimensions [MPa]	Ratio Gross/Net
Abaqus with DNV IS Tol.	169	155	1.090
Abaqus with CN 30.1 Tol.	182	167	1.089
PULS	165	155	1.064
DNV-GL CN 30.1	148	135	1.096
DNV-GL Ship Rules	180 (plate)	159 (plate)	1.132

CONCLUDING REMARKS

Direct application of geometrical non-linear plate theory is the main concept in the new Panel Ultimate Limit State (PULS) stiffened panel models recently recognized by DNV-GL as part of the new rules and standards for ships and offshore constructions. The focus is on assessment of the ultimate capacity limit, rather than the more traditional elastic buckling limit. The method is streamlined for rules based on modern ultimate limit state design principles. The models are validated against non-linear FE analyses. Comparison against existing codes used by DNV-GL Classification Society are also included.

The finite element code ADVANCE ABAQUS has been used in a non-linear buckling analysis of a stiffened deck panel on a single skin tanker that has recently been subjected to a Condition Assessment Program (CAP) hull survey. Further, CAP is a specialized survey program which offers owners a detailed assessment of a ship's actual condition, based on strength evaluation, and fatigue strength analysis as well as a detailed on site systematic inspection of the hull, machinery and cargo systems. With the CAP, owners can be confident that they have an accurate assessment of the ships actual condition, especially as far as the condition compares with the normal Class requirements. The CAP applies, in principle, to oil tankers, chemical carriers and bulk carriers, though other types of ships may be covered, provided that the CAP is properly modified. The CAP consists of two major parts. CAP-MACHINERY/CARGO SYSTEM can be applied in addition to CAP-HULL upon request.

The aim of the analyses has been to validate and compare the capacity estimates obtained from PULS, DNV-GL Classification Notes No.30.1 and the DNV-GL Ship Rules, which all indicated insufficient buckling strength in the deck. Analyses are carried out for both "as built" and DNV-GL Rule net dimensions.

One single uniaxial load case has been investigated. The imperfection tolerances given in the DNV-GL Instruction to Surveyors (DNV-GL IS) and the CN 30.1 have been used as basis for the analyses. For this case the main difference in imperfection tolerances is in the stiffener out-of-straightness, which is over twice as large in the DNV-GL IS as in the CN 30.1 tolerances.

The results show that the PULS code produce capacity estimates in very good agreement with the finite element analysis results based on the tolerance level specified in the DNV IS. It is slightly conservative compared to the finite element analysis results based on the CN 30.1 tolerance level. CN 30.1 buckling strength estimates are conservative compared to the finite element results for both tolerance levels.

Further, as presented in Table 5 the buckling strength in accordance with DNV-GL Ship Rules based on DNV-GL IS initial deflection tolerances gives higher value than ABAQUS finite element analysis. In other words, the buckling strength with DNV-GL Ship Rules based on CN 30.1 initial deflection tolerances gives lower value than ABAQUS finite element analysis.

However, the qualitative impact of the change from "as built" to net dimensions do not comply as well with the finite element analysis results as is the case for the two other formulations.

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