A NEW DESIGN MODEL FOR ULTIMATE AND BUCKLING STRENGTH ASSESSMENT OF STIFFENED PLATES

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ABSTRACT

A new computerised design model for the buckling strength assessment of stiffened panels is presented. The overall formulation is very general, and in principle, any type of stiffening arrangements of open or closed profile type, corrugations etc. can be analysed.

The model is based on an orthotropic version of Marguerre's non-linear plate theory. The stiffened panel is treated as an integrated unit, allowing for internal redistribution of membrane stresses between component plates, while preventing overall buckling and permanent deformations/sets.

By using non-linear plate theory, the strength model is more theoretical consistent than existing code formulations, which are mainly based on empirical curve fitting to a limited number of numerical and experimental results. Complicated items such as bi-axial loading combined with in-plane shear loads and non-linear mode interaction problems are dealt with in a sound physical framework, and empirical approximations are reduced to a minimum.

The model also provides a set of reduced anisotropic/orthotropic macro material coefficients that can be used in refined linear global FE analysis of ship hulls to reflect the increased membrane flexibility experienced by compressed stiffened panels. This area of application allows for redistribution of loads between gross elements such as stiffened panels, frames, girders and bulkheads and ensures a more realistic assessment of the nominal stress flow in a ship hull.

The presented model is planned to constitute the basis for a new DNV buckling procedure for stiffened panels.

KEYWORDS

Strength, Buckling, Postbuckling, Ultimate strength, Stiffened panels, Redundancy, Combined loads

INTRODUCTION

Existing rules, codes and guidelines for buckling design of stiffened panels in ship structures has been developed at a time where it was of main importance to have simple formulas and rule formats convenient for hand calculations. However, simple design rule formulas and codes, presently used by classification societies, consultants and designers, can hardly be expected to cover all the complex items necessary for the optimum and safe design of stiffened panels. Typical complex items are combined load situations, interaction between different buckling modes, effects from of out-of-flatness size and shape, residual stresses, heat affected zones and support conditions. These facts, combined with the present personal computer hardware and software capabilities, makes it possible to develop more modern and direct type of computerised buckling code formulations.

A computerised buckling code must be based on a recognised theoretical basis, and the non-linear thin-plate theories according to von Karman and Marguerre constitute such a set. Adopting these plate theories, special features such as elastic buckling and ultimate strength boundaries, deflections, stiffness properties and three-dimensional buckling mode and stress distributions may be visualised.

The present paper gives a brief introduction to a new computerised buckling code together with a very limited selection of verifications and applications. For a more comprehensive documentation see DNV (2000-seminar), DNV(2001).

PULS – COMPUTERISED BUCKLING MODEL FOR STIFFENED PANELS

General

Buckling of thin-walled stiffened plates is a non-linear phenomenon. However, from a global hull strength perspective, practical design procedures have to be based on linear elastic structural stress analyses with separate buckling checks of local elements. Such linearized design procedures are well established today. Obviously, the linear method will work satisfactory as long as the structure behaves linearly, i.e. as long as buckling failure of local elements is not accepted in any form. Though, to exclude all types of buckling failures of stiffened panels in a hull structure design is rather unrealistic, as it will lead to very conservative scantlings of plates and stiffeners. A design procedure should therefore accept some types of harmless buckling, typically elastic buckling of plate components between stiffeners. The consequence of accepting elastic buckling will be a change of the nominal stress flow in the hull and it is of paramount importance to account for this in the design of the surrounding structure.

In order to provide such a design procedure it is essential that the buckling model describe as closely as possible the real non-linear structural behaviour. To accomplish such a task, a new computerised buckling procedure called Panel Ultimate Limit State (PULS) is proposed. The PULS procedure is a simplified non-linear buckling model for assessing the strength of integrated hull elements. So far it is developed for integrated stiffened flat panels as typically found in ship hulls between frames and girders. It gives strength information at two levels:

i) Elastic buckling and design ultimate capacity of stiffened panels.
ii) Reduced stiffness properties of compressed and buckled panels.

The present PULS procedure is mainly constructed as an Ultimate Limit State design approach, i.e. the stiffened panels is to be designed to resist the most probable highest load during the design lifetime of the ship. The procedure is, however, based on some fundamental design principles, which eliminates certain types of buckling failures and allows others. The purpose behind these principles is to limit the probability for permanent buckles and to constrain the local panel flexibility to stay within reasonable limits. This is in full compliance with the design principles given in existing rules and guidelines of classification societies, e.g. DNV(2000), DNV CN30.1(1995).

Design principles

A consistent design procedure must be founded on some basic design principles, and for the present PULS procedure three main principles apply

i) Elastic local buckling of the component plates in a panel cross-section is accepted.
For open profiles (as analysed as a case study here, Figure 2), local elastic buckling means buckling of plating between stiffeners, sideways/torsional buckling of stiffeners and stiffener web plate buckling. Acceptance of this type of buckling assumes the stiffeners to be strong, see principle iii).

ii) Permanent buckles are not accepted.
By ensuring the maximum membrane stresses within a panel to stay below the yield stress condition (von Mises), permanent sets and buckles are prevented. The maximum membrane stress locations are typical intersections between component plates in a cross-section, and are called hard corners. Maximum membrane stresses are the result of second order stresses from local buckling adding to the direct applied stresses.

iii) Overall buckling of the panel is not accepted.
This principle ensures the panel as a whole (stiffeners) to have sufficient out-of plane bending stiffness to avoid global (overall) buckling. Sufficient overall bending stiffness of the stiffeners ensures lateral support to the component plates, which is a requirement for accepting elastic buckling of local plate components (principle i)).

Theoretical foundation

The present buckling model is based on an orthotropic version of Marguerre's non-linear plate theory, see e.g. Washizu (1975). In its original form, the orthotropic plate theory is not suitable for calculating the buckling strength of thin-walled stiffened panels, since local buckling effects of the component plates in a cross-section is not included. In order to cope with these local buckling modes, separately and in interaction with the overall panel mode, the general orthotropic plate theory is modified. This is done by introducing the concept of reduced orthotropic macro material coefficients.

The PULS procedure is based on a six-dimensional orthotropic macro material law. According to non-linear plate theory this macro material law takes the form of an incremental relation between the in-plane loads (N_1, N_2, N_3) and moments (M_1, M_2, M_3), and the corresponding strains $(\varepsilon_1, \varepsilon_2, \varepsilon_3)$ and curvatures $(\kappa_1, \kappa_2, \kappa_3)$ of a selected reference plane. In mathematical terms the orthotropic macro material law takes the following form

$$\begin{bmatrix} \Delta N_1 \\ \Delta N_2 \\ \Delta N_3 \\ \Delta M_1 \\ \Delta M_2 \\ \Delta M_3 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & Q_{11} & Q_{12} & Q_{13} \\ C_{21} & C_{22} & C_{23} & Q_{21} & Q_{22} & Q_{23} \\ C_{31} & C_{32} & C_{33} & Q_{31} & Q_{32} & Q_{33} \\ Q_{11} & Q_{21} & Q_{31} & D_{11} & D_{12} & D_{13} \\ Q_{12} & Q_{22} & Q_{32} & D_{21} & D_{22} & D_{23} \\ Q_{13} & Q_{23} & Q_{33} & D_{31} & D_{32} & D_{33} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_1 \\ \Delta\varepsilon_2 \\ \Delta\varepsilon_3 \\ \Delta\kappa_1 \\ \Delta\kappa_2 \\ \Delta\kappa_3 \end{bmatrix} \tag{1}$$

In Eqn.1 the symbol Δ indicates incremental quantities. Each of the coefficients in the stiffness matrix can be written as a sum of a linear and a non-linear part as follows:

$$\begin{aligned} C_{ij} &\equiv C_{ij}^{\;L} + C_{ij}^{\;N} \\ D_{ij} &\equiv D_{ij}^{\;L} + D_{ij}^{\;N} \\ Q_{ij} &\equiv Q_{ij}^{\;L} + Q_{ij}^{\;N} \end{aligned} \tag{2}$$

The linear part is given a superscript L symbolising linear fixed values. The non-linear part is symbolised with N as superscript. The latter part is the most interesting as it in addition to the dependency of the applied loads also depends on the level of geometrical imperfections, residual stresses, heat affected zones properties (e.g. in aluminium) etc. Most importantly, they depend on the level of compactness of the thin-walled cross-section.

In order to fully account for the simultaneous growth of both local and global buckling modes in a compressed stiffened panel, a full non-linear iterative solution should be implemented, Steen (1999). However, in order to obtain a more computer efficient and fast procedure, a simplified approach has been chosen here. The simplification amounts to use a fixed set of macro stiffness coefficients evaluated at first hard corner yield. This is a generalisation of the standard effective width approach used in most modern codes. The fixed macro stiffness values are then used as parameters in the overall nominal strength assessment, using the orthotropic buckling theory. It is emphasised that in the present design model we apply the macro tangent stiffness properties rather than the macro secant stiffness properties. This is done in order to cope with the possible severe and unstable interaction between local and overall panel buckling.

Limit states

Five limit state functions have been formulated in order to capture the possible collapse mechanisms in the panel. They are based on stress control against material yield in critical selected hard corner positions, and are typically related to plate and stiffener induced failure modes, as used in DNV/CN30.1(1995), in addition to a plate edge failure control criterion. The limit states are defined as five independent functions

$$f^{(i)}(N_1,N_2,N_3) > 0 \qquad i = 1,2,\ldots,5, \qquad \text{Acceptable} \tag{3}$$

At the limit $f^{(i)}(N_1,N_2,N_3) = 0$, each of the limit state functions describe a surface in load space (N_1,N_2,N_3). The inner envelope of all these surfaces will represent the ultimate design load capacity, Figure 1. The scaling of the loads in this his figure is with respect to the corresponding squash loads.

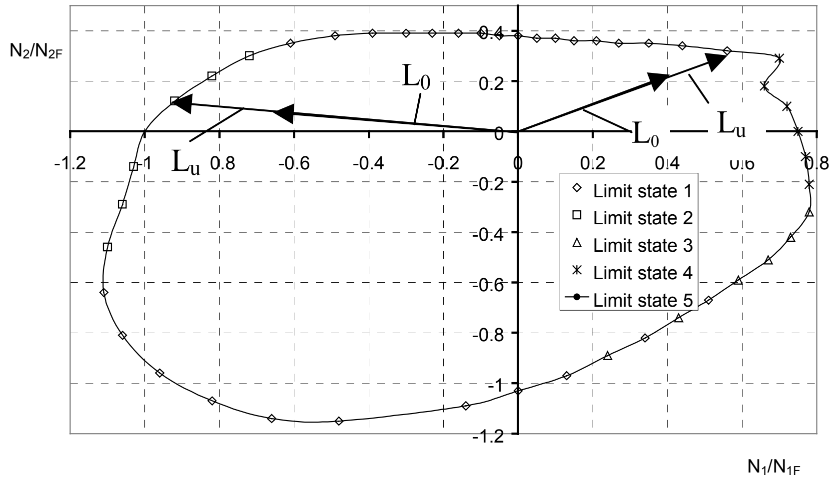

Figure 1: Inner envelope of the five PULS limit states.

For a case by case evaluation of the strength, the distance from the applied load point (N_{10}, N_{20}, N_{30}) to the collapse surface (N_{1u}, N_{2u}, N_{3u}) is evaluated, using a proportional loading history.

The ratio between the applied load radius vector and the corresponding ultimate load radius vector is a direct measure of the safety margin, see Figure 1. In ship rule terminology this safety parameter is referenced to as the usage factor η (inverse of safety factor) and it follows that it is defined as

$$\eta = L_0 / L_u \qquad (3)$$

where the radius vectors L_0 and L_u in load space are defined as

$$L_u = \sqrt{(N_{1u}{}^2 + N_{2u}{}^2 + N_{3u}{}^2)} \qquad (4)$$

$$L_0 = \sqrt{(N_{10}{}^2 + N_{20}{}^2 + N_{30}{}^2)} \qquad (5)$$

The present PULS procedure calculates the actual usage factor η, which is to be measured against the acceptable level given in the rules. This acceptance level will typically be related to the consequence of panel failure. The discussion of acceptance levels belongs to the overall safety philosophy and is a separate topic not discussed here.

VERIFICATIONS OF PANEL STRENGTH

In order to have confidence in a new proposed model for buckling strength assessment, verifications against results obtained with more sophisticated analysis tools are necessary. For this purpose an extensive parameter study of stiffened panels subjected to bi-axial compression/tension loads were carried out using the recognised non-linear finite element code ADVANCE (1999), which is a subset of the well known ABAQUS(1998) code. The examples correspond to double bottom designs used in Bulk and LNG carriers. A full documentation is given in DNV(2000-seminar) from which the LNG carrier example in Figure 2 is extracted.

Figure 2 shows PULS 1.0 predictions together with ADVANCE/ABAQUS results for an out-of-flatness level corresponding to the tolerance levels given for ship structures, DNV/(1995-IS). The comparsions are resonable, but not perfect. One of the main problems encountered when doing non-linear buckling analysis with bi-axial loads, are associated with non-linear mode changes in certain regions of the load space. This effect is seen in the ABAQUS analyses as well as in the more simplified PULS code model and is the main reason for the irregular ultimate buckling boundary presented in Figure 2. The subject of mode change is very complicated and no attempt is made here to discuss it in detail. However, some improvements in the PULS code are needed in this respect.

Added in Figure 2 is also the bi-axial plate buckling criterion in DNV Ship Rules and DNV CN30.1-Chaper 3.4, stiffened panel strength criterion, even though they are not directly comparable. For this example (thick plating; 23 mm) it is noted that for dominating transverse compression, the DNV Ship rules formulas for bi-axial compression, gives optimistic strength estimates compared to both ADVANCE/ABAQUS and PULS results. This can be explained by the fact the DNV ship rules only calculate the strength between stiffeners, thus optimistically assumes that the stiffeners do not buckle. Note that the steel ship rules has an explicit requirement to stiffener moment of inertia for transversely compressed panels, which is not a part of the buckling assessment shown in Figure 2. This criterion is satisfied for the present example.

REDUCED PANEL STIFFNESS IN GLOBAL SHIP HULL ANALYSIS

Studying load-redistribution between gross elements in a ship hull due to buckling can only be solved in full by using non-linear analysis of a large part of the structure. This type of analysis is not dealt with in the present paper, as it requires a separate extensive study. However, by doing a sequence of linear elastic analysis with different levels of stiffness reductions, the consequence of an incrementally and continuously changing local panel flexibility can be simulated in a simplified manner. This is the method used here and results for an outer bottom panel in the double bottom of the LNG Carrier, are illustrated in Figure 2. As documented in DNV(2000-seminar), it is the membrane transverse and coupling stiffness coefficients C_{22} and C_{12} that by far will be most reduced due to elastic local buckling deformations of the plating between stiffeners. In the present example a minimum, an intermediate and a maximum stiffness reduction level of 20, 40 and 60 percent are shown.

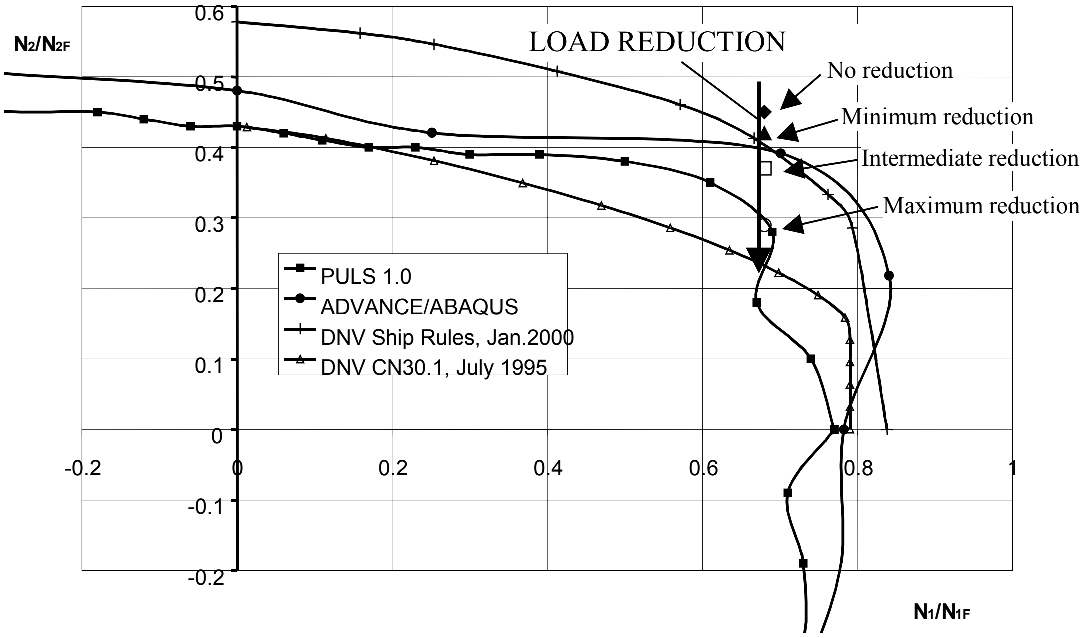

Figure 2: PULS Capacity boundaries curves, and stress check for outer bottom panel in LNG Carrier.

The global effect of these stiffness reductions is seen in Figure 2 illustrating a significant load reduction of the nominal transverse component N_2 (nominal stress σ_2) in the plating. By examining the stresses in the surrounding frame structure it was found that the stress change in the transverse girders were significant, while the stress change in the longitudinal girders was only marginal.

The aim with these studies was to show how linear FE models can be used for global hull redundancy assessment applying a reduced stiffness macro material technique. A main result from the double bottom study was the illustration of how loads redistribute between the plating and girders, as compared to what is normally calculated using the full stiffness standard linear approach. Clearly, due to the cellular construction with longitudinal and transverse frames, the double bottom construction has high torsional stiffness and significant strength reserves were documented. More documentation on this type of analysis, using linear reduced stiffness methods, can be found in Nissen-Lie, Steen & Østvold (1999) and Bakken, Østvold & Steen (2000).

It is concluded that in statically indeterminate plated hull structures, locally prone to plate buckling, global redistribution of forces takes place. The redistribution of forces can be significant and it is of equal importance to assess this effect as to assess the buckling capacity of individual stiffened panels. Further documentation, using sophisticated non-linear finite element programs considering larger parts of ship structures are needed, before firm conclusions on an acceptable design strength approach can be made.

CONCLUSIONS

A new computerised buckling code for flat stiffened panels has been described. The model is based on orthotropic plate theory, which makes the formulation applicable to all types of stiffening arrangements and materials. The results presented and discussed in this paper are for panels with welded open steel profiles.

Computerised buckling codes like the present PULS model has the obvious benefit of predicting more closely the real non-linear structural behaviour than existing rules and guidelines. This gives an improved basis for weight optimisations, together with a more consistent control of the safety margin against failure. It also provides additional valuable information, i.e. typically buckling mode shapes, elastic buckling and failure boundaries in load space, stress distributions and stiffness properties.

The present PULS code is based on some basic design principles in order to constrain the panel designs to have some minimum stiffness properties for efficient in-plane load transfer. Design principles for control of maximum stresses and prevention of permanent sets and buckles are also implemented. These design principles are consistent with the rules and guidelines given by classification societies today, even though in the latter they are not explicitly stated and not consistently included for complex load situations.

As a step in the direction of developing more consistent procedures for redundancy strength assessments of larger parts of hull structures, a reduced stiffness approach using coarse linear FE models, has been tested. This method has so far not been verified against large size non-linear analysis of ship hulls, but it is believed to capture the main physical effects. Future verification of this approach will rate its possible usefulness as a simple and practical approach for global hull strength assessment.

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