BUCKLING STRENGTH OF STIFFENED PANELS CONSIDERING ACTUAL GEOMETRIC IMPERFECTIONS

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Abstract. *Full scale measurements of geometric imperfection distributions on stiffened panels during ship construction were carried out and then incorporated to a numerical model to better simulate the buckling failure mechanism. Inter-frame longitudinally stiffened panels are modeled and then submitted to in-plane axial compression in order to describe the ultimate strength and post-buckling behavior. Initial geometric imperfections of the full-scale geometry were obtained using laser tracker equipment, which is a portable contact measurement system employing laser technology with sub-millimeter accuracy. The numerical models are represented by shell elements assuming finite membrane strains and large rotations, considering both geometric and material nonlinearities. Comparative studies were then performed to evaluate the influence of two different imperfection distributions on the buckling behavior: maximum imperfection acceptable by the codes and actual imperfection distribution measured at the shipyard for the ship bottom plates.*

Keywords: buckling strength, stiffened panels, geometric imperfections

1. INTRODUCTION

Floating platforms and ships hulls are constituted, basically, by stiffened panels. The fabrication of these structures involves heating induced by both cutting and welding processes. These procedures generate geometric imperfections and residual stresses on the panels and can have a detrimental effect on the panels' strength. Compressive loads during life cycle of these structures are significant. Therefore, there are uncertainties related to the panel structural behavior, mainly in relation to the buckling associated with different geometric imperfection distributions.

Buckling analysis of stiffened plates subjected to axial compression has received considerable attention. In general, the main factors governing the buckling behavior are boundary conditions, geometric properties, load combinations and material properties. Research works have been conducted for many years to better understand the influence of geometric imperfections on the integrity of marine structures panels.

Faulkner (1975) has shown that the governing parameter of the collapse of a steel plate is the slenderness. However, the importance of the initial imperfections has been also widely documented. Pasqualino et al. (2001) evaluated the upper limit resistance of stiffened panels using the finite element method. Gordo and Guedes Soares (2002) concluded that the collapse mode is the determinant factor on thin plate's strength. Amante and Estefen (2010) compared the residual buckling strength results from a damaged semisubmersible platform column with the ultimate strength of equivalent intact column to estimate the safety margin associated with the column structural capability after supply vessel collision. In this study the initial imperfections and the collision damage were incorporated in the buckling analyses. These studies were accomplished with idealized imperfections, however measurements of actual imperfections in shipyards represent an important advance in this research area. Amante and Estefen (2011) also performed numerical and experimental simulations for small scale damaged stiffened panels. The damage was imposed with a local indentation on the panels. Measurements of the geometric imperfection distributions and damage shapes in the small scale stiffened panels were accomplished using the equipment laser tracker. The numerical-experimental correlation analyses show that numerical models are able to simulate adequately the buckling behavior of both intact and damaged stiffened panels.

In Figure 1 the difference between the idealized imperfections and the measured imperfections is shown.

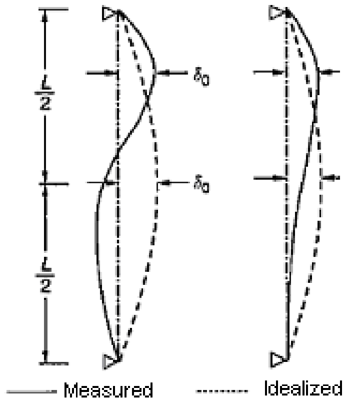

Figure 1: Measured and idealized geometric imperfections.

New measurement technologies could be employed in the shipyards to better understand and quantify these geometric imperfections.

2. NUMERICAL-EXPERIMENTAL CORRELATION

Studies on numerical-experimental correlation were performed in order to calibrate numerical models to be used for verify the ultimate strength of ship bottom panels. Similar studies were accomplished by Estefen et al. (2007), where the techniques employed for the fabrication of the models are presented.

Small scale steel models representatives of flat panels from bulk-carrier ship bottom were fabricated in scale 1:14. Equivalent dimensional tolerances as recommended for full scale panels were obtained for the small scale models. Longitudinal stiffeners have been used in a model representative of longitudinally stiffened panels between web frames. Figure 2 shows the small scale stiffened panel. In Tables 1 and 2 are indicated, respectively, plate and stiffener dimensions.


Figure 2: Small scale stiffened panel

Table 1: Plate dimensions (mm)

Longitudinal length	178
Transversal length	268
Thickness (t)	1.03
Space between stiffeners (b)	53.6

Table 2: Stiffeners dimensions (mm)

Web thickness	0.77
Web height	21.6
Flange thickness	1.03
Flange width	7.10

Initial imperfections due to fabrication were measured using the laser tracker equipment. It’s a portable measurement system with sub-millimeter accuracy. Plates and stiffeners imperfections were considered. The equipment is showed in Figure 3 during the mapping of a small scale model. Figure 4 presents the plates of a small scale model with their initial imperfections amplified by 20 times.

Figure 3: Measurement of the small scale model

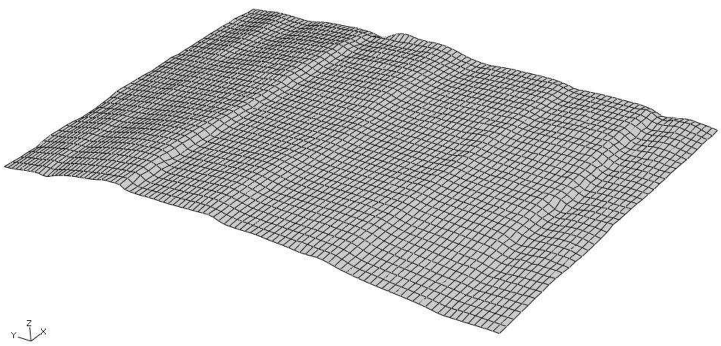

Figure 4: Initial imperfection distribution of the plates (amplified 20 times)

Numerical simulations were performed with the finite elements program ABAQUS (2008). The numerical models are represented by shell elements assuming finite membrane strains and large rotations, considering both geometric and material nonlinearities. The measured geometric imperfections distributions are imposed on the models. Compressive load in form of prescribed displacements was applied incrementally in the longitudinal direction until the panel buckling and, further, in the post buckling regime, where the following boundary conditions were assumed: Ux = 3 mm, Uy = Uz = 0 and θx = θy = θz = 0. Along the edge opposite to the applied compression edge, the fully clamped condition was assumed: Ux = Uy = Uz= 0 and θx = θy = θz = 0. Material stress-strain curve obtained from tensile tests was provided as input to the finite element program. Yield stress (σ_o) and Young modulus (E) are 315 N/mm² and 207,863 N/mm², respectively. A mesh sensitivity study was performed in order to define the most appropriate mesh refinement for the subsequent ultimate strength analyses. The mesh refinement was defined with 45 elements along the length and 18 elements between longitudinal stiffeners. Along the stiffener web height and flange width 8 and 2 elements were considered, respectively. The adopted mesh for the panel numerical modeling is presented in Figure 5.

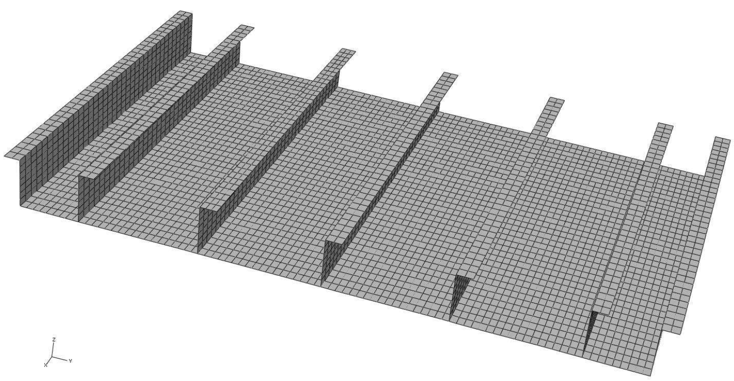

Figure 5: Mesh adopted for the numerical analyses

3. RESULTS FOR NUMERICAL-EXPERIMENTAL CORRELATION

Two compressive tests with intact panels have been carried out. The instrumentation of the models was performed using strain-gages. Two biaxial strain-gage (longitudinal and transversal directions) and two uniaxial strain-gages (longitudinal direction) were used. Strain-gage positions are shown in Figure 6. The compression tests were performed in an Instron machine, model 8802.

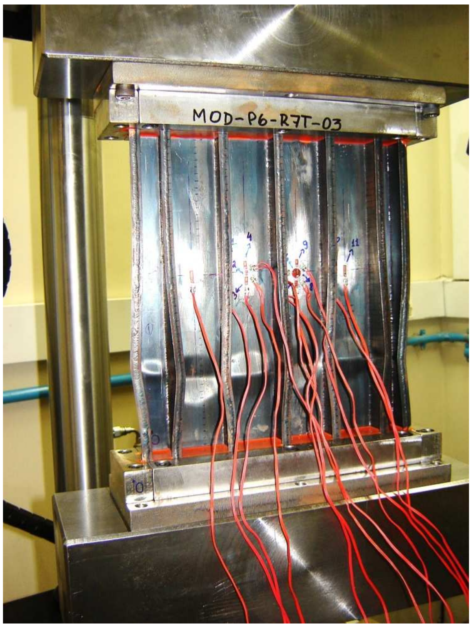

Figure 6: Instrumentation of the small scale panel

After the compression tests and the numerical analyses the results were compared. Curves force versus axial displacement from numerical and experimental simulations for model 1 are shown in Figure 7. Very good accordance was obtained up to the buckling failure. In the post-buckling regime the numerical results presented higher values after a steeper drop in capacity of the experimental model. Afterwards the unloading followed parallel paths. The main difference is associated with a tendency observed in both models 1 and 2, with a steep strength drop just after the buckling load for the experimental curves and a steadier unloading for the numerical curves. For the intact panels the highest buckling loads were obtained for the experimental models with 1.6% and 1.0% higher than the numerical values. Post-buckling modes for the model 1 are presented in Figures 8 and 9 for both experimental and numerical models. Results show a similar behavior for both small scale models.

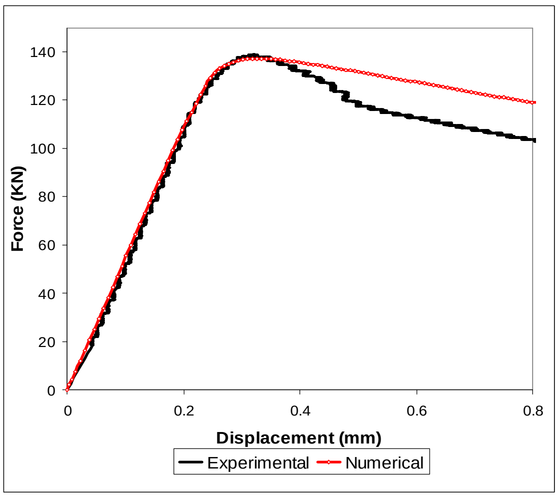

Figure 7: Applied force versus axial displacement - Model 1

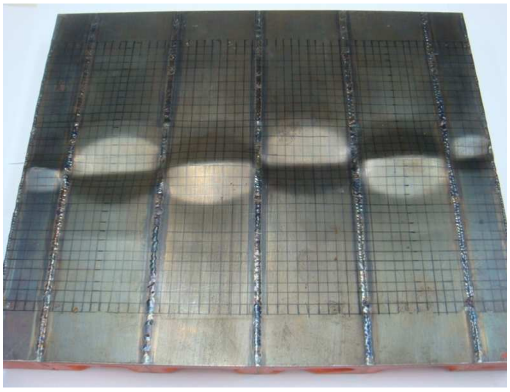

Figure 8: Experimental buckling mode - Model 1

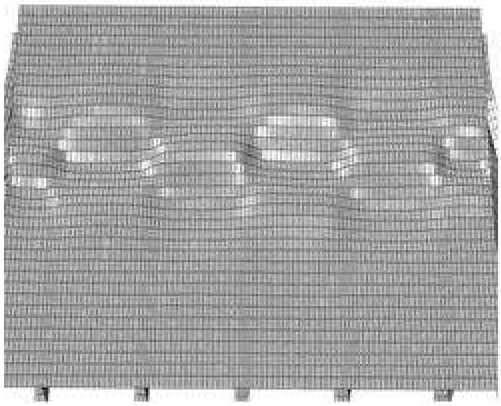

Figure 9: Numerical buckling mode - Model 1

4. STRUCTURAL BEHAVIOR OF SHIPS UNDER BENDING

The position of the wave in relation to the ship hull girder has a considerable influence on the distribution of the buoyancy along the ship length. A wave of length equal to the length of the ship moving along the ship can occupy a variety of positions. The first one considers the crests at the perpendiculars. In this condition the ship will sag, with the deck in compression and the bottom in tension, as shown in Figure 10. The other condition considers the crest amidships. In this condition the ship will hog, the deck being in tension and the bottom in compression, as shown in Figure 11.

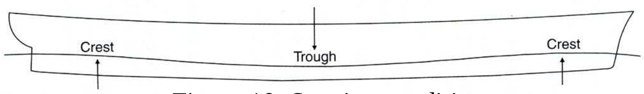

Figure 10: Sagging condition

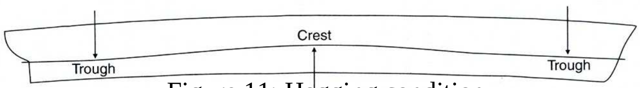

Figure 11: Hogging condition

Due to described loads, the region more liable to higher compressive and tensile stresses is the amidships, specifically the panels further from the neutral surface. Failure tends to occur first in regions where stresses are compressive due to buckling of the panels at bottom and deck. Therefore, aiming an analysis of ultimate strength of panels, derived from hogging condition, the region chosen for the measurement of geometric imperfections was the bottom plating amidships. The load at these panels is assumed to be uniaxial due to the hogging condition. Measurements were performed between web frames spaced 2.40 meters.

5. MEASUREMENT OF INITIAL IMPERFECTIONS IN A SHIPYARD

Distortions generated by the fabrication process, the initial geometrical imperfections, are quantitatively represented by the distance of the actual surface from the idealized one assumed for design purposes. Initial geometrical imperfection is generated by processes as cutting, welding and forming. This type of imperfection, characterized by the shape and amplitude of the distribution, is the main cause of different buckling loads in nominally identical panels.

During the period of ship bottom construction, a team from the Subsea Technology Laboratory (COPPE/UFRJ) performed measurements on the bottom panels of a Panamax bulk-carrier ship at a Brazilian shipyard. Measurements were performed in selected panels in order to obtain the geometric imperfections. Laser Tracker equipment was used in the measurements of geometric imperfection. This equipment presents an accuracy of 0.01 mm for measurements at distances of 10 meters and 0.12 mm at distances of 70 meters, Figure 12.

Figure 12: Measuring equipment – Laser Tracker

Measured panels were located amidships between transverse girders. Two types of panels were measured. Figure 13 shows the frontal view of the measured region. In Figure 14 is showed an isometric view of the region and are pointed the measured panels. In Figure 15 is showed a measured plate result amplified 20 times. Panels present the following dimensions: Panel with three stiffeners: length (a) of 2400 mm, spacing between stiffeners (b) of 785 mm and plate thickness (t) of 14.5 mm. Panel with four stiffeners: length (a) of 2400 mm, spacing between stiffeners (b) of 750 mm and plate thickness (t) of 14.5 mm. Stiffener dimensions: thickness web (t_w) of 11 mm, web height (h_w) of 300 mm, flange width (b_f) of 90 mm and flange thickness (t_f) of 16 mm. Figure 16 presents the generated panels.

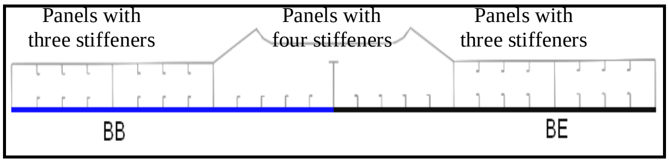

Figure 13: Measured region.

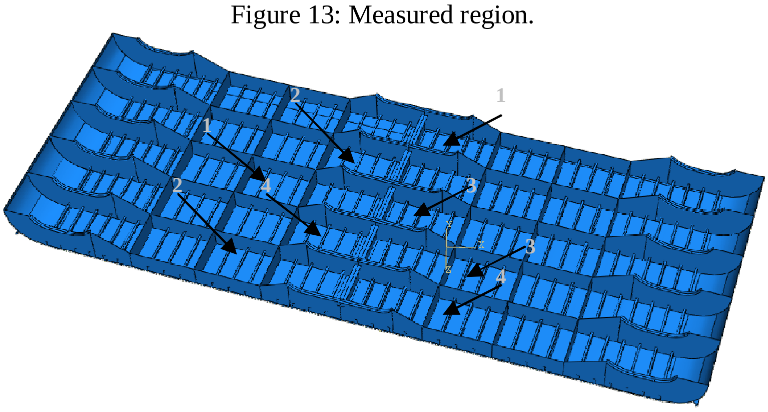

Figure 14: Measured panels – Isometric view

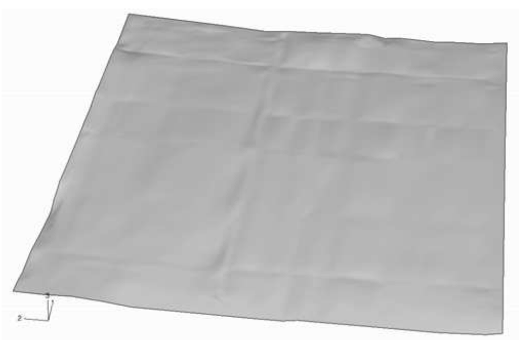

Figure 15: Plate with measured imperfection distribution (amplified 20 times)

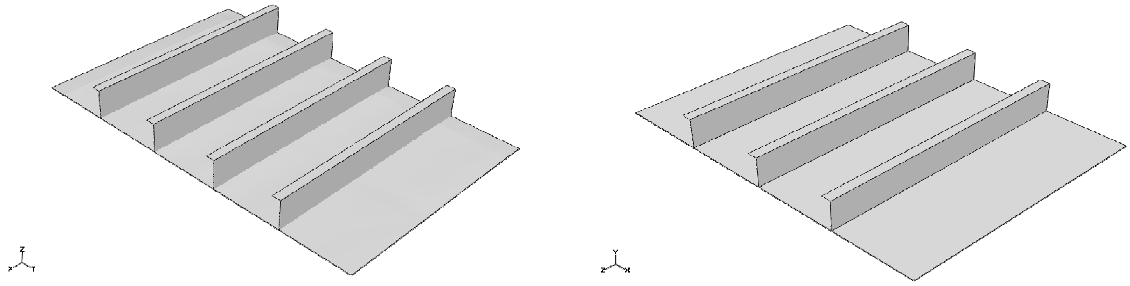

Figure 16: Generated panels

6. NUMERICAL ANALYSIS

The aim of the numerical analysis is to compare the panel buckling strength for two different imperfection distributions, actual imperfections and idealized ones assuming the buckling natural mode and the maximum amplitude allowed by DNV (2004). Additionally, the obtained results are compared with the DNV recommendations.

The panels with the actual imperfections were generated with the measurements carried out in the shipyard, as already presented in the previous section.

In the next step it was generated panels presenting imperfection distributions following the buckling natural modes. Two natural modes were considered in the analyses. Figure 17 shows the distribution with two half waves in the longitudinal direction (NM=2). It was also analyzed the distribution with three half waves in the longitudinal direction (NM=3).

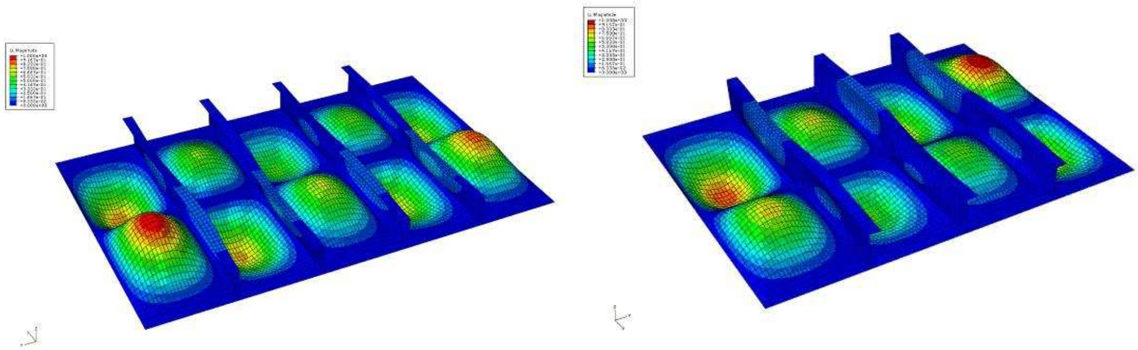

Figure 17: Imperfection distribution (NM=2).

Plates with imperfections following the buckling natural mode have been assumed the value for maximum imperfection amplitude (δ) based on the DNV recommendations, i.e. δ equal to 0.5% of the spacing between longitudinal stiffeners, Figure 18.

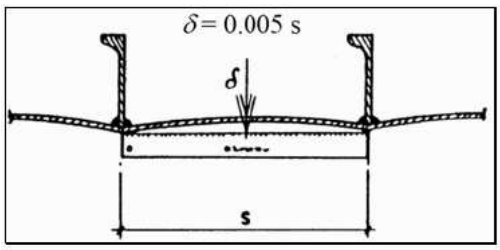

Figure 18: DNV - maximum amplitude recommendation.

Therefore, a value of 3.925 mm was adopted for the panels with three stiffeners and 3.750 mm for the panels with four stiffeners. For the measured panels the value of δ is between 1.653 mm and 4.752 mm, therefore some plates are presenting imperfections amplitude above of the DNV recommendation.

Numerical analysis has been performed with ABAQUS computer program version 6.8 Hibbit et al. (2008), based on nonlinear finite element method. Compressive load in form of prescribed displacements (10 mm) was applied incrementally in the longitudinal direction for the panel buckling fail and, further, the post buckling regime, where the following boundary conditions were assumed along the load edge: $U_x = 10$ mm, $U_y = U_z = 0$ and $\theta_x = \theta_y = \theta_z = 0$. For the opposite transversal edge, the fully clamped condition was assumed: $U_x = U_y = U_z = 0$ and $\theta_x = \theta_y = \theta_z = 0$. Note that U_x, U_y and U_z represent the displacement along x, y and z and θ_x, θ_y and θ_z, rotation about x, y and z axis. Along the longitudinal borders were assumed: $U_y = U_z = 0$ and $\theta_y = \theta_z = 0$. The panels have been modeled using shell elements. A mesh sensitivity study was performed in order to define the most appropriate mesh refinement for the subsequent ultimate strength analyses.

Material and geometric nonlinearities were considered in the analyses. The material adopted is steel with yield stress 315 N/mm^2 and Young modulus 207,860 N/mm^2. Different imperfection distributions on the plates that form each panel with four stiffeners are presented in the Figure 19. These imperfections cause differences in the buckling strength and collapse modes for the panels. In Figures 20 and 21 are showed the collapse modes for panels 1 and 2, respectively. It is observed a different collapse mode for each one of these panels.

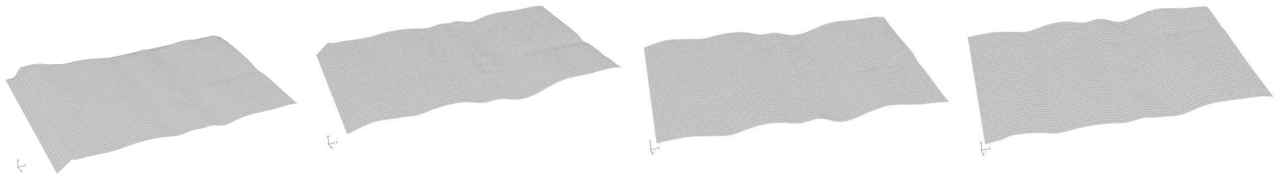

Figure 19: Imperfections distribution panel 1 and 2 (four stiffeners).

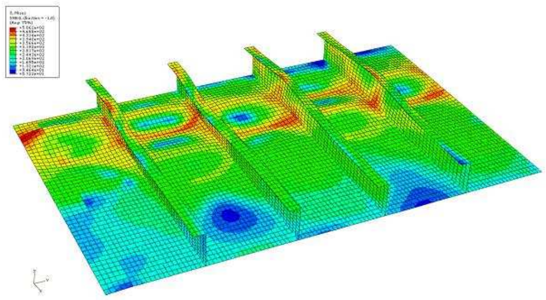

Figure 20: Collapse mode – Panel 1

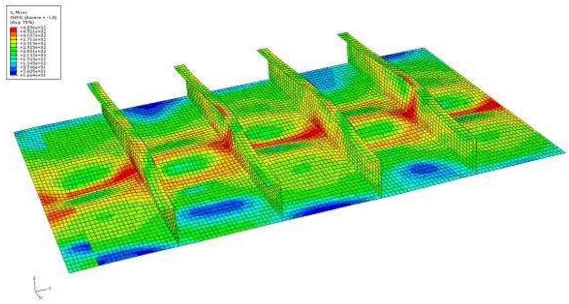

Figure 21: Collapse mode – Panel 2

Tables 1 and 2 present the ultimate strength results of stiffened panels with actual imperfections and imperfection with natural mode distribution and maximum DNV amplitude. It is observed that panels with actual imperfections present higher compressive strength even if the maximum measured imperfection amplitude is above the DNV recommendations. It is important to mention that actual imperfections can also generate significant strength difference between panels. However, chosen panels haven't presented high difference. The greatest one, 4.75%, can be observed between the stiffened panels with four stiffeners 1 and 2.

Table 1: Panel buckling strength (MPa) – 4 stiffeners

Measured Imperfection	Strength	DNV
Panel 1	18.49	16.69
Panel 2	19.37	16.69
Panel 3	19.16	16.69
Panel 4	18.63	16.69
Natural Mode Panel	Strength	DNV
Panel MN=2	19.11	16.69
Panel MN=3	17.63	16.69

Table 2: Panel buckling strength (MPA) - 3 stiffeners

Measured Imperfection	Strength	DNV
Panel 1	14.84	13.21
Panel 2	14.83	13.21
Panel 3	14.71	13.21
Panel 4	14.60	13.21
Natural Mode Panel	Strength	DNV
Panel MN=2	15.18	13.21
Panel MN=3	13.90	13.21

7. CONCLUSIONS

A correlation study has been performed using the results from small scale experiments and numerical simulations in order to establish the numerical model to be used in full scale simulations.

During the period of ship construction, a team from the Subsea Technology Laboratory (COPPE/UFRJ) performed full scale measurements of the geometric imperfection distributions on stiffened panels of a Panamax bulk ship in a Brazilian shipyard.

The paper studied the influence of different geometric imperfection distributions on the buckling behavior of stiffened panels with actual imperfections, based on nonlinear finite element analyses.

The magnitude of the initial geometric imperfections confirmed the influence of this parameter on the axial buckling load. However, the greater influence on the ultimate strength is from the initial imperfection distribution mode. Initial distortion mode coincident with the natural buckling mode of a particular plate generates lower bound buckling load. On the other hand, some imperfection modes can difficult the buckling failure, therefore generating upper bound values for the respective buckling loads.

In the analyzed panels the obtained results show that DNV recommendations are conservative. Even when the measured panels presented maximum imperfection magnitude bigger than DNV recommendations the buckling strength of these panels have presented higher ultimate strength compared with similar panel with natural mode imperfections.

Full scale measurements of the geometric imperfection distributions on actual marine structures during the construction could contribute to a better understanding of buckling failure mechanism. The association of the numerical models, as presented in this paper, with new equipment already available for accurate dimensional measurements of plate distortions can represent a step forward in the understanding of the buckling behavior of complex marine structures.

8. ACKNOWLEDGEMENTS

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