RESIDUAL STRENGTH OF OFFSHORE STRUCTURES DAMAGED BY COLLISION

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Abstract. *Despite the efforts to reduce accidents involving ship collisions, they continue to happen. The aim of this paper is to compare the ultimate buckling strength of intact and damaged offshore structures after a collision event. Two structures were evaluated, a semi-submersible platform column damaged by a supply vessel collision and a ship bottom hull damaged by a rock. The intact analysis were accomplished with the finite element program ABAQUS. The numerical models were represented by shell elements assuming finite membrane strains and large rotations, considering both geometric and material nonlinearities. Geometric imperfections were represented by a sinusoidal expression based on the recommendations of a classification society. The finite element analysis of a collision accident involves material and geometric high nonlinearities, large rotations and deformations, friction and complexities in the contact and interactions between two structures. Nowadays with the development of advanced computer technology and sophisticated finite element packages it is feasible to accomplish this type of analysis with relatively high accuracy. ABAQUS program was used to carry out the dynamic collision simulation. Residual strength results from the damaged structures were compared with the ultimate strength of equivalent intact one to estimate the safety margin associated with the structural capability after the collision.*

Keywords*: offshore structures, collision, buckling, residual strength*

1. INTRODUCTION

Experiences with offshore and other structures show that ship grounding and collision represent significant hazards. This applies both with respect to loss of human lives, severe environmental consequences and economical loss. With the increasing demand for safety at the sea and for protection of the environment, it’s very important to observe the collision accidents and analyzes their consequences. A local damage due to the collision mustn’t cause a global structural failure, i.e. local damage is allowed and the design criterion ensures robustness ensuring that a small damage does not escalate into disproportionate consequences through a progressive failure that could lead to a global structural failure.

In the last International Ship and Offshore Structures Congress (2006), it was concluded that the offshore industry has been using simplified structural models for the calculation of the energy absorption associated with collision. Thus, it was recommended to use more sophisticated tools such as the nonlinear finite element method so that structural responses during and after a collision could be more precisely predicted. Some recent studies utilized the nonlinear finite element method to analyze ship collisions (Nolau Netto et al. 2004, Tornqvist 2003, Orguc et al. 2006).

Therefore, the purpose of the paper is to study the response and the residual buckling strength of offshore structures after a collision event. Two structures were evaluated, a semi-submersible platform damaged by a supply vessel collision and a ship bottom hull after a vertical impact in a rock. Residual buckling strength results from both damaged structures are compared with the ultimate strength of equivalent intact one to estimate the safety margin associated with the structural capability after the collision.

For many years research works have been conducted to better understand the main factors governing the buckling behavior of plates and stiffened plates. The main aspects like boundary conditions, load combinations, geometric and material properties and fabrication imperfections have been studied, but the integrity of marine structures damaged panels after impact loads seems to be another area which the designers need some additional insight.

Estefen and Harding (1983) evaluated the structural behavior of the ring stiffened column of the first TLP platform, installed in the Hutton field, considering initial distortions and residual stresses. After this study, Estefen et al. (1987) accomplished a parametric study on the residual strength due to buckling behavior of large diameter ring stiffened floating platform affected by supply vessel collision using a nonlinear computer program. They obtained a detrimental effect of collision around 11%.

2. FABRICATION IMPERFECTIONS

In the buckling analysis the fabrication imperfections influence the collapse behavior and must be considered, therefore the column of the semisubmersible platform and the ship bottom hull were modeled using a CAD software to facilitate the work of describing the structures and creating an automatic way to implement and vary the initial geometric imperfections. Mode and amplitude of geometric imperfections can cause substantial reduction in the buckling strength of the stiffened panels which constitute the structures. These imperfections are assumed with the distribution represented by the sinusoidal expression:

$$w(x;y) = W_{\max} \cdot \sin\left(\frac{m \cdot x \cdot \pi}{a}\right) \cdot \sin\left(\frac{n \cdot y \cdot \pi}{b}\right) \tag{3}$$

Where,

w - out-of-plane displacement at the control point;
$W_{\max}$ - maximum panel out-of-plane displacement;
x - longitudinal position of the control point;
y - transverse position of control point;
m - number of longitudinal imperfection half-waves;
n - number of transversal imperfection half-waves;
a - plate longitudinal length;
b - plate width.

Column geometry presents the following dimensions. Outer shell with: panel length of 3000 mm between the decks and web frames, except in the first and last part of the column that presents panel length of 2500 mm. Plate thickness is 19 mm. Longitudinal bulkheads and decks present thickness of 12 mm. Space between longitudinal stiffeners is 625 mm. Stiffeners dimensions: web thickness of 12 mm, web height of 250 mm, flange thickness of 19 mm and flange height of 90 mm. Web frames: T 1000 mm x 300 mm x 12 mm x 12 mm.

The ship bottom hull geometry presents the following dimensions. Panel length of 2400 mm. Space between longitudinal stiffeners of 750 mm. Plate thickness is 16.5 mm. In Figure 1 is shown the models.

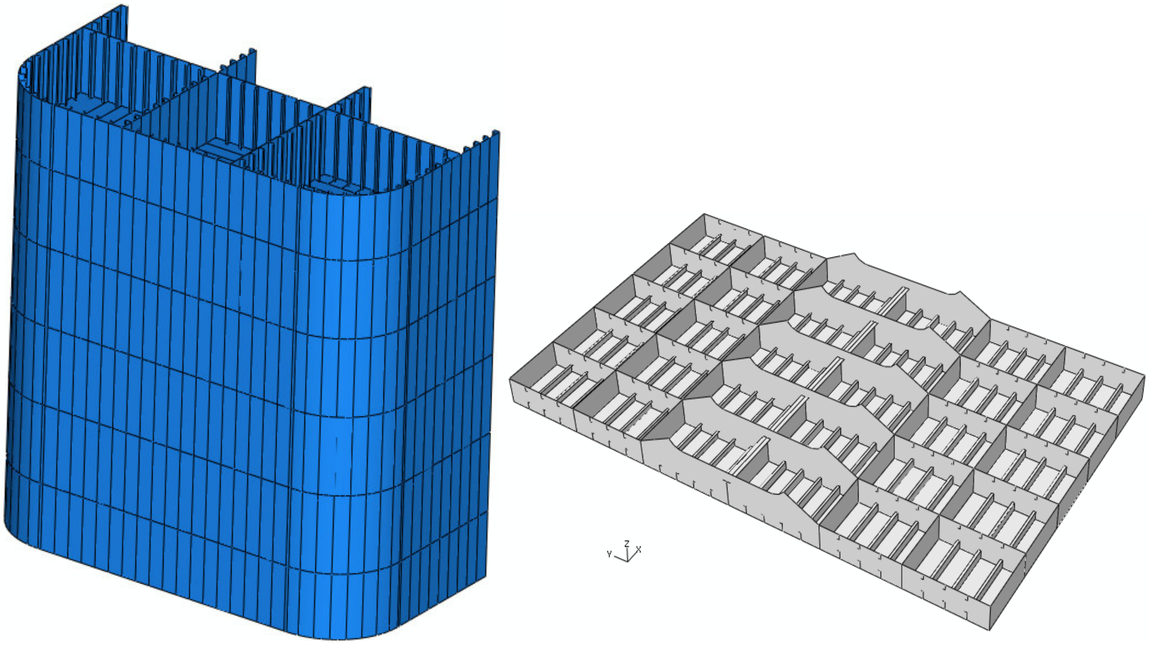

Figure 1. Column and Ship Bottom Models

It's assumed the value for maximum imperfection amplitude (W_{max}) based on the DnV (2005) recommendation, which means W_{max} equal to 0.5% of the spacing between longitudinal stiffeners. Therefore, a value of W_{max} equal to 3.125 mm was adopted for the column and 3.75 mm for the ship bottom.

In all analysis, material and geometric nonlinearities were considered. The material adopted for the platform is the steel typically employed nowadays in the semi-submersible platform construction with yield stress of 390 N/mm^2 and Young modulus of 210,000 N/mm^2 and the material employed for the ship bottom hull analysis presents yield stress of 315 N/mm^2 and Young modulus of 210,000 N/mm^2. Material stress-strain curve was used for the numerical simulations. Influence of the strain rate on the material behavior was not considered in this work. All analyses were modeled using shell elements with four integration points.

3. INTACT ANALYSIS

In order to adjust the numerical models to be used for the ultimate buckling strength studies of full scale panels, numerical-experimental correlations with small scale panel models were accomplished at the Subsea Technology Laboratory – COPPE/UFRJ. The numerical-experimental correlations and fabrication techniques are detailed in Estefen et al. (2006) and Trovoado and Estefen (2007).

The finite element program ABAQUS/Standard was used in order to carry out the intact buckling analysis. The numerical meshed models used are shown in Fig. 2. Due to symmetry condition only a quarter of the column was analyzed. The mesh employed was based on the previous numerical-experimental correlation.

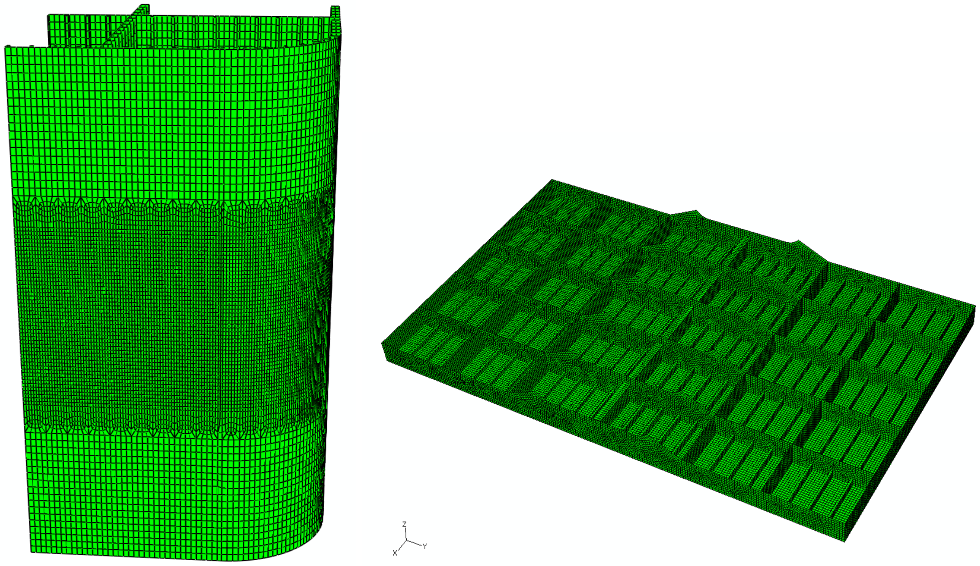

Figure 2. Numerical meshed models

3.1. Intact column results

Compressive load in form of prescribed displacements was applied incrementally at the extreme top nodes reaching the column buckling and, further, the post buckling regime, where the following boundary condition was assumed: $U_x = U_y = 0$, $\theta_x = \theta_y = \theta_z = 0$. For the extreme bottom nodes, the fully clamped condition was assumed: $U_x = U_y = U_z = 0$, $\theta_x = \theta_y = \theta_z = 0$.

Obtained results are shown in terms of force versus the applied displacement for the buckling of the whole column, Fig. 3. It is observed that the structural failure occurs for a buckling load of 1,005MN. For cumulative incremental displacement 25.8 mm, it is observed a drop in strength followed by another peak associated with structural capacity recovery. It happens initially due to the bulkheads loss of axial structural strength, but the outer shell compensates the drop resisting additional axial load.

Outer shell von Mises stress distribution can be seen in Fig. 4 for the axial displacement associated with the bulkhead buckling load. At the same axial displacement the bulkhead failure associated with elasto-plastic buckling can be observed in Fig. 5. The outer shell buckling regime is established beyond the applied axial displacement 29.8 mm. In Fig. 6 is shown the outer shell initial strength drop. In Fig. 7 is presented an outer view of the column plating post-buckling mode. In all Figures of the column the von Mises stress are presented in Pascal (Pa).

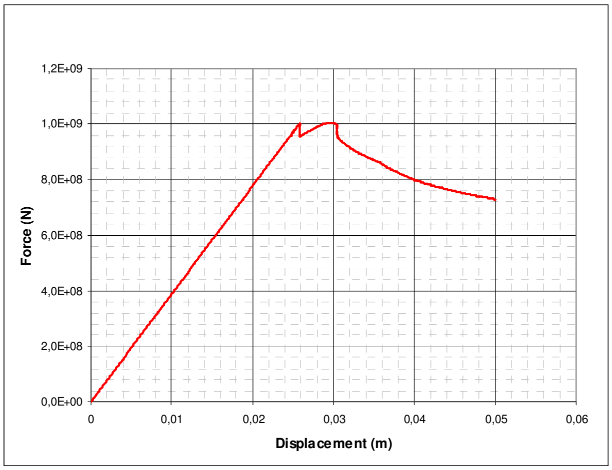

Figure 3. Force versus displacement for the intact column.

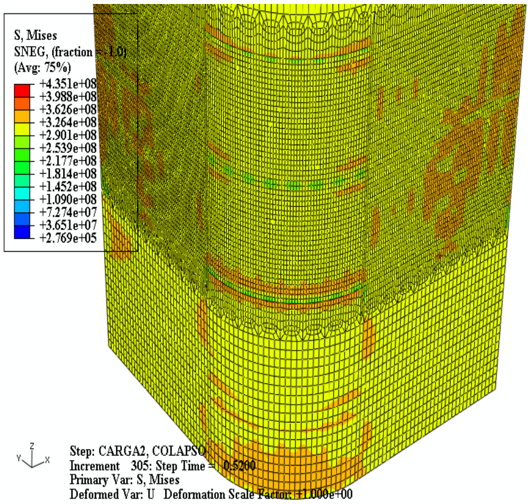

Figure 4. Outer shell von Mises stress (Pa) distribution

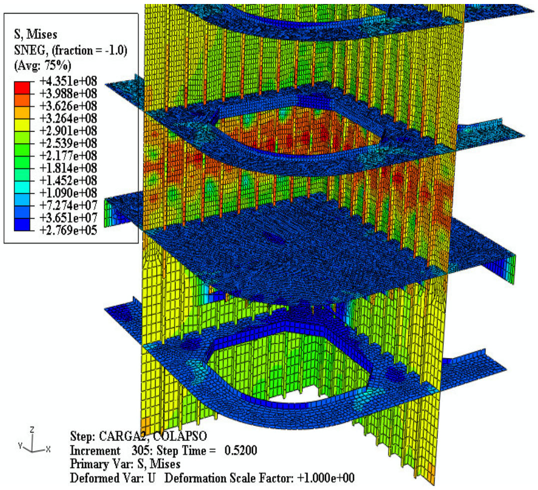

Figure 5. Bulkhead buckling

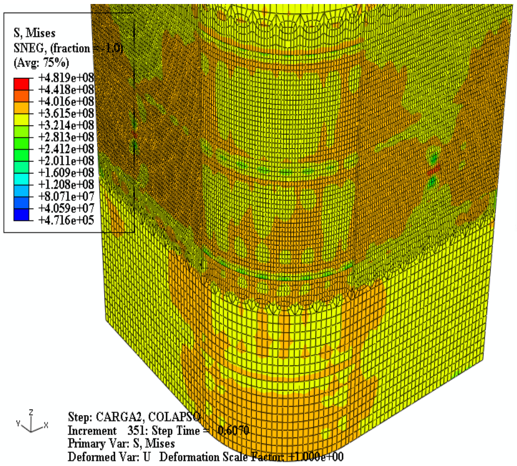

Figure 6. Initial post-buckling regime

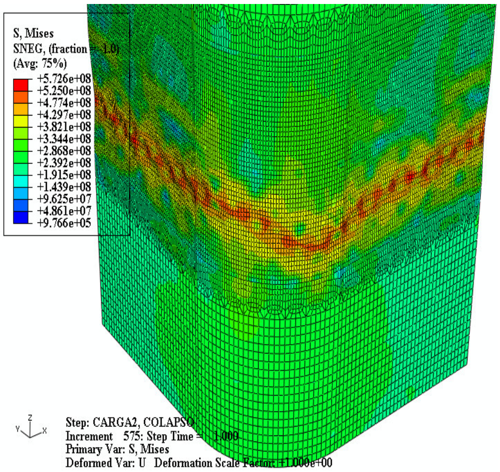

Figure 7. Post-buckling collapse mode

3.2. Intact ship bottom results

Compressive load in form of prescribed displacements was applied incrementally at the extreme front nodes reaching the panel buckling and post buckling regime. In these nodes the boundary condition was assumed: $U_y = U_z = 0$, $\theta_x = \theta_y = \theta_z = 0$. For the extreme back nodes, the fully clamped condition was assumed: $U_x = U_y = U_z = 0$, $\theta_x = \theta_y = \theta_z = 0$. The structural failure occurs for a buckling load of 108 MN. In Figure 8 the obtained results are shown in terms of force versus the applied displacement. In Figure 9 is shown the post buckling regime of the intact ship bottom.

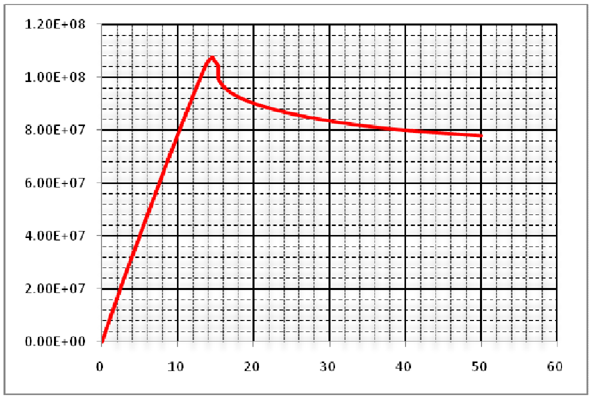

Figure 8. Force (Newton) versus displacement (mm) for the intact ship bottom hull.

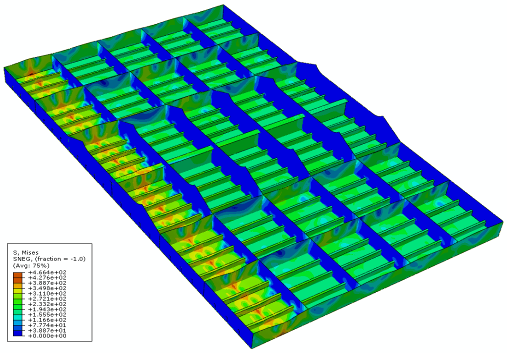

Figure 9. Post buckling regime of the intact ship bottom (von Mises stress in MPa)

4. COLLISION ANALISYS

The finite element analysis of a collision accident involves material and geometric high nonlinearities, large rotations and deformations, friction and complexities in the contact and interactions between two structures. Nowadays, with the development of advanced computer technology and sophisticated finite element packages, it is feasible to accomplish this type of analysis with relatively high accuracy. In this paper, the program ABAQUS was used to carry out the dynamic collision simulation. The explicit code solver used by ABAQUS provided a powerful tool for a fast solution of this nonlinear collision problem.

Rupture criterion was not considered in the analysis. For typical ship structures, the stress state is tri-axial, complicating the development of proper rupture failure criteria. There are various proposed approaches to handle tri-axial rupture failure. However, the validation of the available approaches is very limited, especially for actual structural configurations. Further studies are recommended by ISSC2006 (2006) for proper rupture modeling principles in nonlinear finite element analysis.

4.1. Column collision results

For the collision analysis of the column, restriction was imposed for translation and rotation in all directions at extreme bottom and top nodes. Characteristics of the supply vessel involved in the collision are based on DnV (2005) recommendations. The vessel displacement is 5,000 ton and the fluid force was included as additional mass. Only the part of the supply vessel that collides with the platform was modeled. The region next to the midship section was chosen due to its geometric regularity. Finite element model is presented in Fig. 10, where the supply was modeled with quadrilateral rigid elements. This type of element was used to assume very high stiff for the vessel. Thereby all the potential impact energy is assumed to be absorbed by plastic and elastic deformations of the platform column. The large collision energy on the column caused high localized effects on the structure in terms of geometric deformations and stress concentrations. In Figure 11 are shown the deformed outer shell and a large deformation on the longitudinal bulkhead. All figures are plotted to indicate von Mises stress distribution.

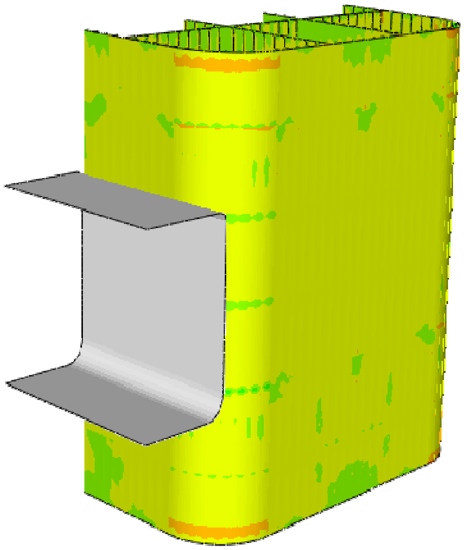

Figure 10. Supply vessel model

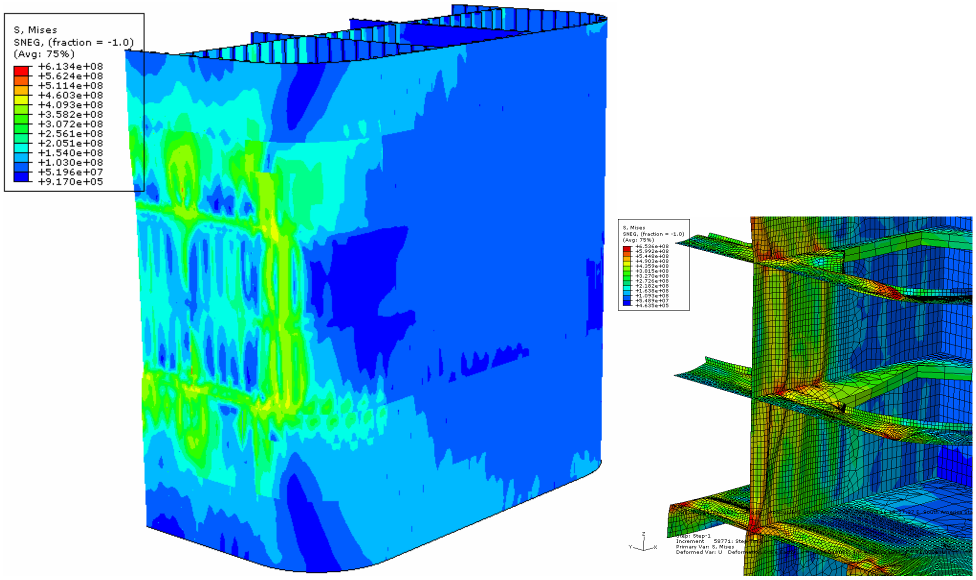

Figure 11. Von Mises stress (Pa) in the outer shell and large internal deformations

4.2. Ship bottom collision results

The ship bottom hull was damaged by a collision in a rigid body representing a rock. The local damage was accomplished with a low speed representing an impact with 0.25 m/s vertical speeds. For the impact analysis, fully clamped condition was imposed for translation and rotation at extreme side nodes, and symmetry condition was applied for the extreme front and back nodes. In Figure 12 are shown the local of the collision and the damage. It's observed a small damage in the ship bottom hull. It occurs due to the low impact energy involved in the collision.

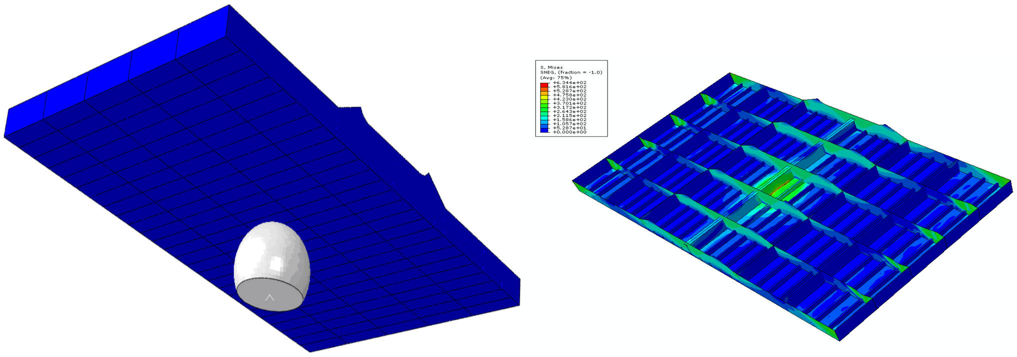

Figure 12. Damage caused by the collision (von Mises stress in MPa)

5. RESIDUAL BUCKLING STRENGTH ASSESSMENT

Finally, the results obtained from the collision were utilized as a predefined field, therefore representing the initial configuration of the damage structures. Compressive load was applied incrementally in form of prescribed displacements at the extreme top nodes until the structures reaches the peak load and then, further, in the post-buckling regime. The same boundary conditions applied for the intact structures analysis were assumed in this analysis.

5.1. Residual strength results of the column

Structural failure occurs for the buckling load of 960 MN. In Fig. 13 is presented the post-buckling mode for the column, damaged by the collision, under axial loading. Comparison between intact and damage models indicates the detrimental effect of 4.50%. It was observed a large reduction of axial structural resistance in all plates and stiffeners in the collision region.

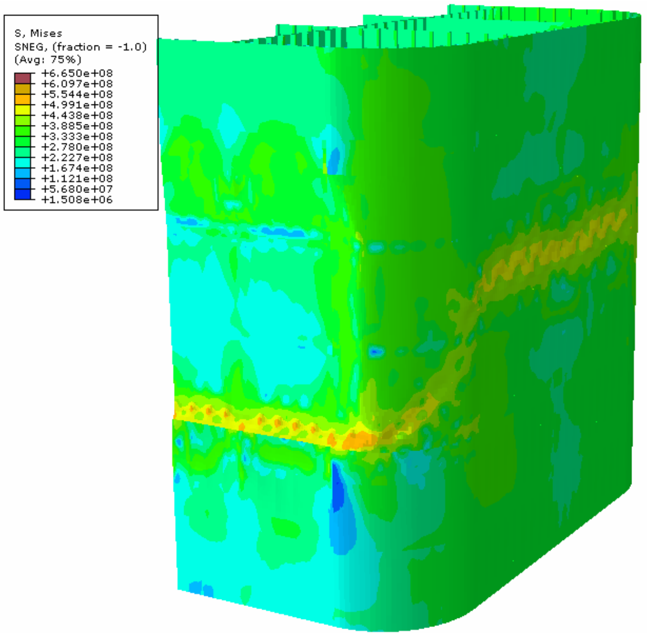

Figure 13. Post-buckling mode of the column damaged by the collision under axial loading (von Mises stress in Pa)

5.2. Residual strength results of ship bottom

Structural failure occurs for the buckling load of 104 MN. In Fig. 14 is presented the post-buckling mode for the damaged ship bottom hull, under axial loading. The low energy damage changed the post-buckling mode in the hull, but the comparison between intact and damage models indicate the detrimental effect of 4% only.

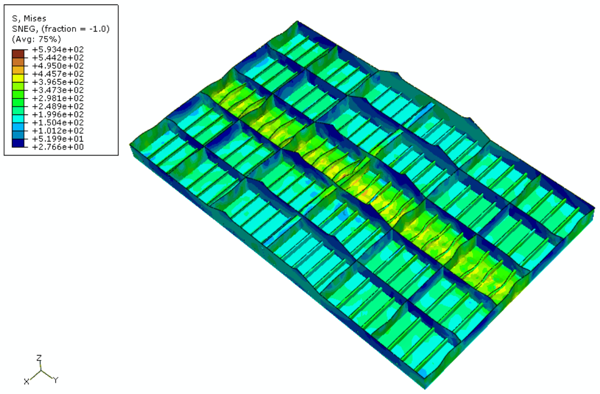

Figure 14. Post-buckling mode for the damaged ship bottom hull (von Mises stress in MPa)

6. CONCLUSION

Finite elements simulations were performed considering material and geometric nonlinearities, initial fabrication imperfections, friction and contact formulations in order to investigate the detrimental effect of the damage caused by collisions in offshore structures.

The residual strength after collision is 4.50% less than the intact structure for the column and 4% for ship bottom. However, depending on the impact energy involved, additional loss of strength can be expected. Therefore, special care shall be taken during the design stage to prevent serious consequences. Despite of the results obtained, the platform studied presents a large safety margin for the in-plane compressive load. However, other collisions scenarios and different structural arrangements must be analyzed to better understand the residual strength mechanism of failure following a collision.

The uncertainty of the frequency and magnitude of the accidental loads associated with the possibility of structure buckling show that analysis of accidental load effects shall be accomplished more deeply in the design stage. The results can be used as an indicator of the severity of offshore collision and provide insight to lower bound safety factor to deal with such common accidents.

Possibility of optimized arrangements for the column members close to splash zone should be further investigated to prevent serious collision effects on the column structural integrity.

7. REFERENCES

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8. RESPONSIBILITY NOTICE