NON-LINEAR FINITE ELEMENT ANALYSIS OF DECK, BOTTOM AND INNER BOTTOM PANELS IN FPSO VESSEL

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ABSTRACT

Floating production, storage and offloading systems (FPSOs) are widely used to develop offshore oil and gas fields. FPSOs structures shall be evaluated in order to satisfy the specifications of both in-service and pre-service loading conditions. The key aspects of the structural assessment of FPSOs are the buckling and ultimate strength behaviour of plate panels, stiffened panels and hull girders. The focus of this paper is to address the buckling and ultimate strength criteria for FPSO hull structures. Buckling strength assessment of three panels in FPSO vessel is being carried out using the non-linear finite element code ADVANCE/ABAQUS, where the analyses involve both material inelastic effects and non-linear geometric effects. The capacities of the bottom panels are estimated under simultaneously acting lateral pressure and axial compression. The upper deck is only subjected to axial compression. The three panels are located in the upper deck, the inner bottom and the bottom shell. The capacities of the bottom panels are predicted under simultaneously acting lateral pressure (0.249 MPa for inner bottom and 0.146 MPa for the bottom) and axial compression. For both the bottom and the inner bottom panel the pressure acts from the ballast tank and outward. The upper deck is only subjected to axial compression. The Ultimate Limit State (ULS) capacities have been estimated to 260 MPa for the upper deck, 205 MPa for the inner bottom and 250 MPa for the bottom shell.

Keywords: Non-linear finite element, FPSO vessel, axial compression, lateral pressure, buckling capacity

1. Introduction

Because of its attractive features, floating production, storage and offloading systems (FPSOs) have been widely used to develop offshore oil and gas fields. These are often ship-shaped, either converted from current or purpose-built tankers, and the hull structural scantling concept for tankers may be applicable to FPSOs. Nevertheless, the FPSOs have their own special characteristics. FPSOs are situated at unique locations where dynamic loading is somewhat different from those resulting from unregulated service conditions. Structures shall be evaluated in order to satisfy the specifications of both in-service and pre-service loading conditions. The key aspects of the structural assessment of FPSOs are the buckling and ultimate strength behavior of plate panels, stiffened panels and hull girders.

Ship and offshore structures consist of continuous panels stiffened by stiffeners and supporting members. As Hughes and Paik (2010) [8] have pointed out, ship panels may be subjected to a range of operational loading components (static and wave-driven) that act on the structure, such as: biaxial tension / compression, edge shear and in-plane bending, which are mainly driven by overall hull girder bending and torsion. Lateral loading of the container comes from the water pressure and the weight of the cargo. While the extreme value of each variable does not occur simultaneously, it interacts with each other, influencing the ultimate response to the force interaction.

Mechanical response to ship hull plates and stiffened panels has been studied for decades. As pointed out by the ISSC Committee [7], it is not possible to determine the true margin of structural safety under extreme loads if the ultimate strength remains unknown. As there is a high degree of geometric nonlinearity and material nonlinearity before and after the ultimate strength capacity has been reached, non-linear elastoplastic FE analysis is one of the preferred methods for limiting state based assessment. The main influence factors for such calculations are: (a) geometric factors; (b) plasticity-related material parameters, including strain hardening and fracture; (c) initial manufacturing and welding deficiencies; (d) residual damage stress; (e) temperature factors and (f) strain-dependent response.

Over the last years, the ultimate strength response of panels under pure shear loading has earned some research focus. Alinia (2005) [2] carried out a study on the optimization of stiffeners in shear-loaded plates, followed by Alinia and Dastfan (2006) [3] who studied the effect of the surrounding components (i.e. beams and columns) on the overall behavior of thin steel shear walls. They conclude that the flexural stiffness of the surrounding members has no significant effect, either on the elastic shear buckling or on post-buckling behaviour. The torsional rigidity only affects the elastic buckling load greatly, and the extensional stiffness marginally affects post-buckling efficiency.

Gheitasi and Alinia (2010) [9] studied the slender classification of unstiffened metal plate under shear loading, dividing it into slim, moderate, and stocky groups in another study. Zhang et al. (2008) [17] developed a simple formula for the final shear strength of the plates and verified against Abaqus (2014) [1] FE results and a large number of published results. They also evaluated the suitability of the application for a model for a stiffened panel structure depicting an oil tanker's side shell. From the strong correlation obtained, they concluded that the stiffened panel's ultimate shear strength could be calculated by examining a single plate of the same thickness with limits clearly endorsed and edges restricted to stay straight.

Paik et al. (2001) [13] developed relationships with long and/or short steel plate elements subject to a combination with four load components, namely longitudinal compression / tension, transverse compression / tension, edge shear, and lateral pressure loads, in terms of ultimate strength formulations. It is assumed that the plate element is supported simply along all (four) edges held straight.

Paik (2005) [12] investigated the ultimate shear force reduction characteristics of steel plates due to local denting damage. The harm was modeled as initial geometric deformation without taking the residual stresses or strains into account. He found that the overall shear strength of the plate decreases dramatically as the dent diameter increases, and that the worst condition occurs when the dent is situated at the center of the plate.

Paik et al. (2003) [14] used nonlinear FE experiments to investigate the ultimate strength under axial compressive loads of dented steel plates. As in his shear loading work, the damage was seen as an initial stress-free deformation in the mesh. They found that as the location of the dent is closer to the edge of the unloaded plate the ultimate force decreases relative to the central spot. Raviprakash et al. (2012) investigated the effect of different dent parameters (dent length, dent width, dent depth and orientation angle of the dent) on the ultimate static strength of thin square plates of different thicknesses under uniaxial compressive load.

Rizzo et al. (2014) [11] conducted a parametric FE study with a stiffened panel similar to the previous research and noted that as the thickness value increases, the stiffened panel's ultimate strength appears to be closer to the plate. They also observed that higher values of initial imperfection amplitudes (based on the first buckling mode) result in lower limit state values, as predicted.

Xu and Soares (2013) [16] have conducted quasi-static nonlinear FE analyzes for stiffened panels under compressive damage loading including the residual stress and dent deflections caused by indentation. It has been found from the case study carried out that the residual stress caused by the indentation marginally affects the ultimate strength of the considered dented stiffened panels.

Ozguc (2019) [10] performed buckling strength assessment of a deck of a double hull oil tanker by using the non-linear finite element code ADVANCE ABAQUS. The comparisons were 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 was under axial compression. Two levels of imperfection tolerances were 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 were analyzed. The strength values from ADVANCE ABAQUS and PULS were very close. DNV-GL CN 30.1 was in conservative side, but the strength differences between the “as built” and “net” dimension cases were consistent with the finite element analysis results. The finite element code ADVANCE ABAQUS was employed in a non-linear buckling analysis of a stiffened deck panel on a double skin tanker that was subjected to a Condition Assessment Program (CAP) hull survey. The aim of the analyses was 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.

In this study, buckling strength assessment of three panels in FPSO vessel is being carried out using the non-linear finite element code ADVANCE/ABAQUS, where the analyses involve both material inelastic effects and non-linear geometric effects. The capacities of the bottom panels are estimated under simultaneously acting lateral pressure and axial compression. The upper deck is only subjected to axial compression. The three panels are located in the upper deck, the inner bottom and the bottom shell. The capacities of the bottom panels are predicted under simultaneously acting lateral pressure (0.249 MPa for inner bottom and 0.146 MPa for the bottom) and axial compression. For both the bottom and the inner bottom panel the pressure acts from the ballast tank and outward. The upper deck is only subjected to axial compression. The Ultimate Limit State (ULS) capacities have been estimated to 260 MPa for the upper deck, 205 MPa for the inner bottom and 250 MPa for the bottom shell.

2. Plate Geometry

Representative deck, inner bottom and bottom panels has been selected as shown in Figure 1, with dimensions given in Table 1, Table 2 and Table 3, respectively. Net scantlings have been used in the analysis.

Table 1. Dimensions of the upper deck panel.

Length of panel (L_1)	5700 mm	
Number of stiffeners	15	
Stiffener spacing (s)	975 mm	
Stiffener height (h)	400 mm	
Flange width (b_f)	100 mm	
Stiffener type	Angle	
Material type	HT32	
	"As-built"	Net
Thickness web (t_w)	13.0 mm	11.0 mm
Thickness flange(t_f)	18.0 mm	16.0 mm
Thickness plate (t_p)	20.0 mm	19.0 mm

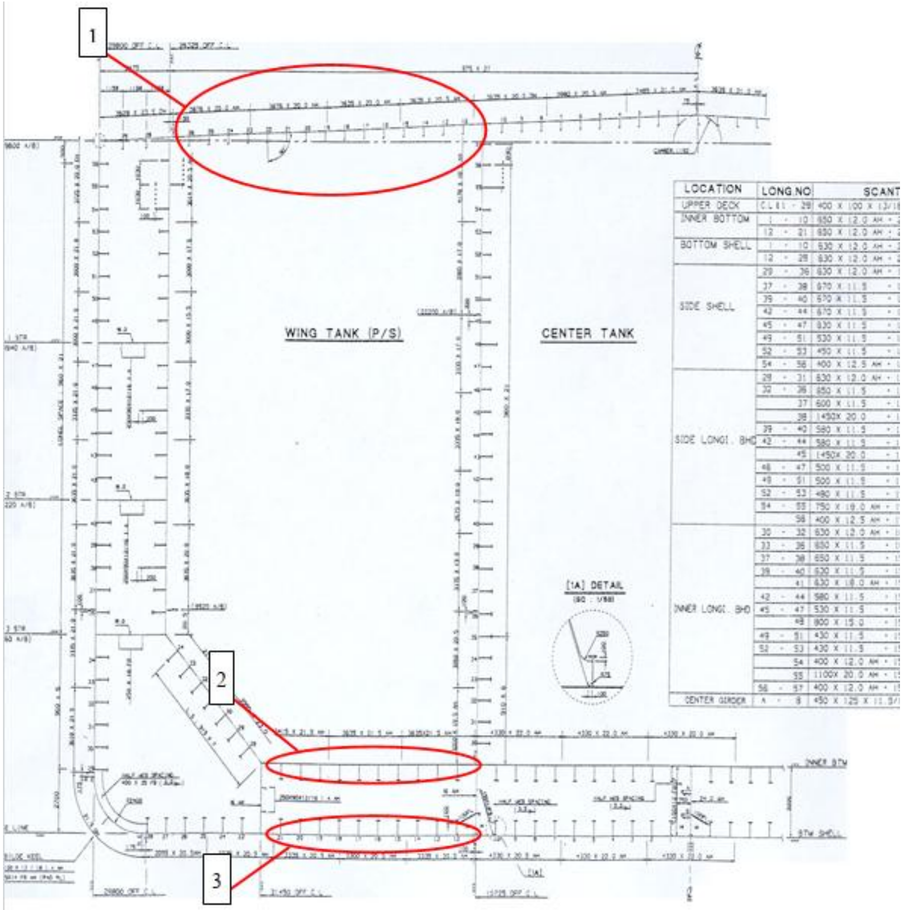

Figure 1. Cross-section of the FPSO vessel with identification of the upper deck (1), the inner bottom (2) and the bottom shell (3).

Table 2. Dimensions of the inner bottom panel

Length of panel (L_1)	5700 mm
Number of stiffeners	10
Stiffener spacing (s)	975 mm
Stiffener height (h)	677 mm
Flange width (b_f)	200 mm

Stiffener type	T	
Material type	HT32	
	"As-built"	Net
Thickness web (t_w)	12.0 mm	10.5 mm
Thickness flange(t_f)	27.0 mm	25.5 mm
Thickness plate (t_p)	21.5 mm	20.0 mm

Table 3. Dimensions of the bottom shell panel

Length of panel (L_1)	5700 mm	
Number of stiffeners	10	
Stiffener spacing (s)	975 mm	
Stiffener height (h)	656 mm	
Flange width (b_f)	200 mm	
Stiffener type	T	
Material type	HT32	
	"As-built"	Net
Thickness web (t_w)	12.0 mm	10.5 mm
Thickness flange(t_f)	26.0 mm	24.5 mm
Thickness plate (t_p)	20.5 mm	19.5 mm

3. Load Combinations

The buckling strength of the panels must as far as possible be assessed with a simultaneously acting lateral pressure load consistent with the ULS load condition. This will be the ULS ballast condition (hogging) for the bottom and inner bottom panels.

The pressures acting on the bottom and the inner bottom panels are 0.146 MPa and 0.249 MPa, respectively, acting from the ballast tank side of the panels. These are the values used in the global finite element analysis and are results from the direct load transfer from DNV GL WASIM program [4]. DNVGL WASIM software is a proven tool for hydrodynamic analysis of fixed and floating vessels with or without forward speed, including calculation of global motions and local pressure loading on the vessel. It solves the fully 3-dimensional radiation/diffraction problem by a Rankine panel method. Further, important non-linear effects can be included in the analysis. This can be of importance also for offshore structures.

It is assumed that there is no pressure acting on the deck panel.

4. Finite Element Model

To prevent the collapse of the panel to be initiated at the boundaries of the models, the models represent three frame spacings (1/2+1+1+1/2) in the direction of the stiffeners. In the transverse direction, the models represent the full panel between primary longitudinal members.

Transverse frames are not be explicitly modelled, but their presence are reflected by the boundary conditions as described below.

The models of the bottom panels have six elements between stiffeners, 36 elements between transverse frames, five elements across the web height and two elements across the width of the flange. The model of the deck has the same number of elements in each direction except for four elements across the web height.

A bi-linear elasto-plastic material model with kinematic hardening is applied in the analysis. The material parameters are as follows;

Young's modulus, E [N/mm^2]	206 000
Poisson ratio, ν	0.3
Yield stress [N/mm^2]	315
Strain hardening parameter, E_T [N/mm^2]	1000

5. Boundary Conditions

Boundary conditions are imposed on the edges and lines as indicated in Figure 2. Symmetry conditions are given on edges B1 and B2. This might represent a constraint on the deformation of the plate and on the web and flange of the stiffener, but experience from other similar analyses [10] indicates that this has small impact on the results. Edge B2 is fixed in 1-direction. Edge B1 is free to move in this direction, but with the edge constrained to remain straight and follow the deformation of corner node 1.

Edges B3 and B4 are fixed in the lateral direction and in the rotation about the 2- and 1-axis. The latter is to keep the panel from collapsing too early in one of the outermost plate fields. Edge B4 is fixed in the 2-direction, while edge B3 is free to move in this direction, but with the edge constrained to remaining straight and follow the displacement of corner node 1.

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

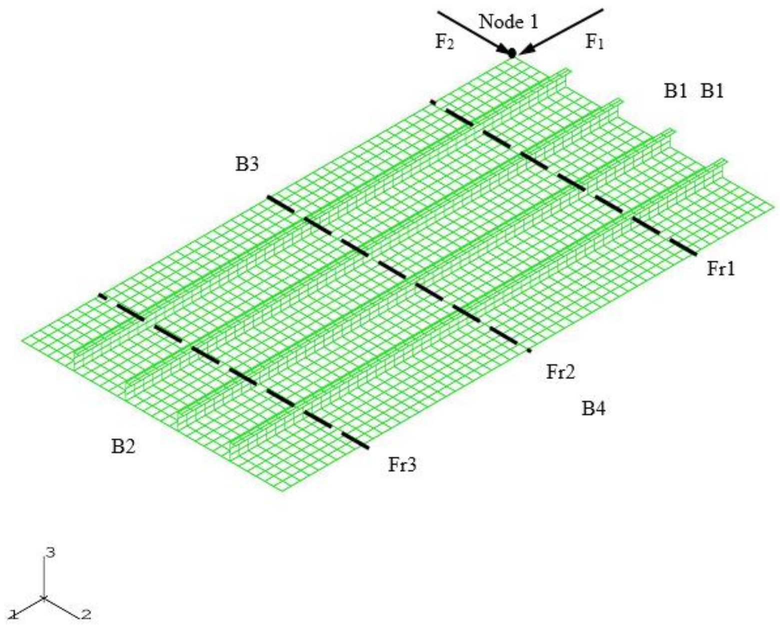

Figure 2. Typical stiffened panel model with labelled boundaries and indication of frame locations.

6. Initial Imperfections

The local geometrical imperfection pattern is prescribed as a combination of a short-waved and long-waved pattern. This does not necessarily fit the imperfection shapes found in practice, but ensures conservative estimates of the ultimate buckling strength.

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. Magnified illustrations of the resulting total imperfection shape are shown in Figure 3, Figure 4and Figure 5.

The imperfections used in the FE models are consistent with the IACS tolerance requirements [5].

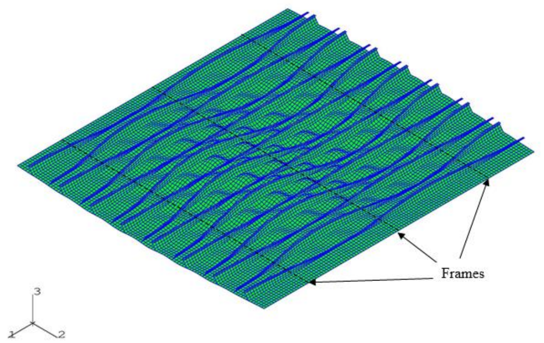

Figure 3. Imperfections in the upper deck multiplied by 50.

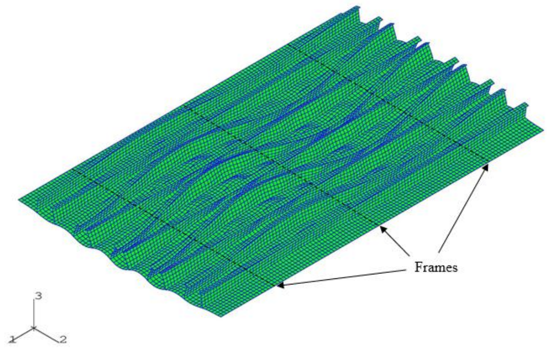

Figure 4. Imperfections in the inner bottom multiplied by 50

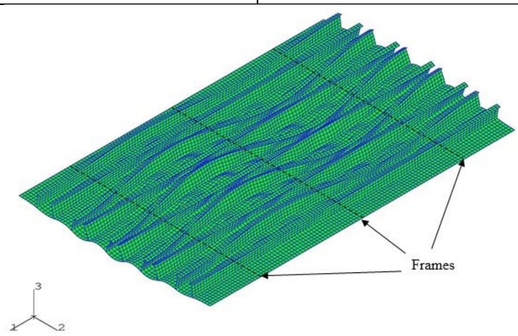

Figure 5. Imperfections in bottom shell multiplied by 50.

7. Loads and Load Application

All analyses are performed in load control, i.e. the non-linear solution is found by incrementing the magnitude of a specified load combination. Automatic load incrementation using the Riks solution algorithm is used to be able to trace the equilibrium curves past limit points [1].

In the two cases in the bottom where the panel is loaded in a combination of axial stress and lateral pressure, the loads are applied in two load steps. First, the lateral pressure is incremented to the specified magnitude in the first load step. In the second load step, the in-plane loads are incremented with the lateral pressure kept fixed.

In-plane axial loads are applied as a point load in corner node 1 (see Figure 2), which is the master node for the displacement of the edges B1 and B3. The constraint equations will ensure that the loads are distributed along the edges as necessary to make the edges remain straight.

8. Finite Element (FE) Results

The results based on the earlier described assumptions are presented in Table 4. The calculated capacity represents the maximum registered load in the analysis, identified as the collapse state in Figure 6. Design capacities should be obtained by applying the relevant usage factor given in the rules.

Table 4. Buckling capacities calculated by ADVANCE/ABAQUS

Panel identification	Applied pressure	Calculated capacity
1) Upper deck	0 Mpa	260 MPa
2) Inner bottom (ballast)	0.249 Mpa	205 MPa
3) Bottom shell (ballast)	0.146 Mpa	250 MPa

Figure 7 to Figure 9 show the deformed panels with von Mises equivalent stresses at the collapse-state defined in Figure 6.

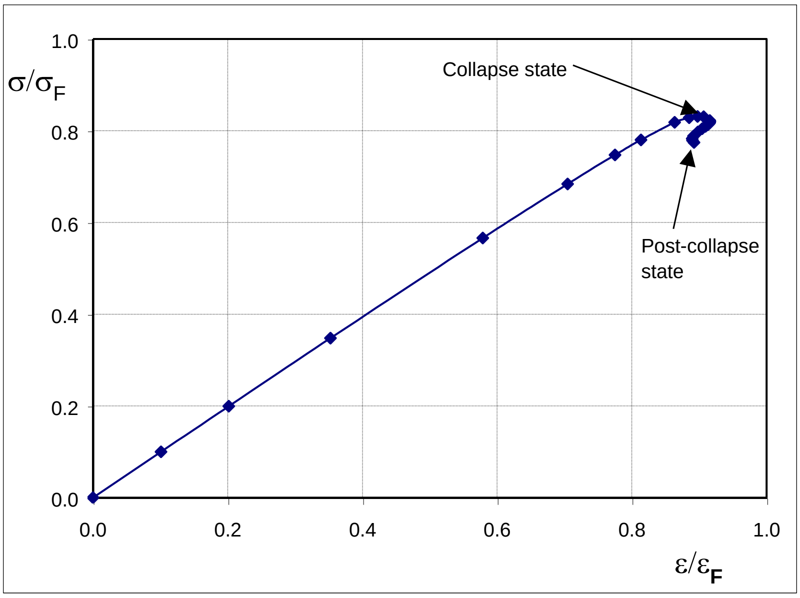

Figure 6. Load-displacement curve for the upper deck panel (σ_F = yielding strength)

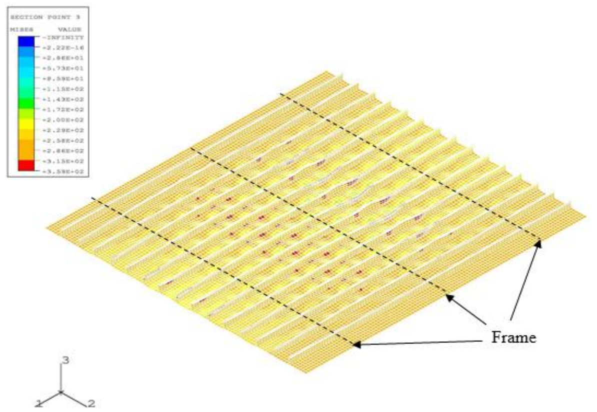

Figure 7. Deformation and stress in inner deck panel at collapse. Magnification 10x.

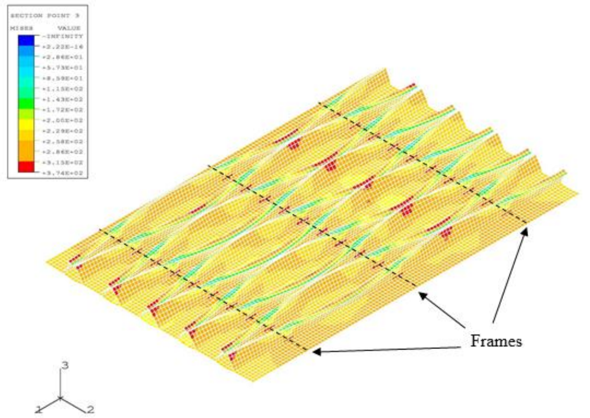

Figure 8. Deformation and stress in inner bottom panel at collapse. Magnification 10x.

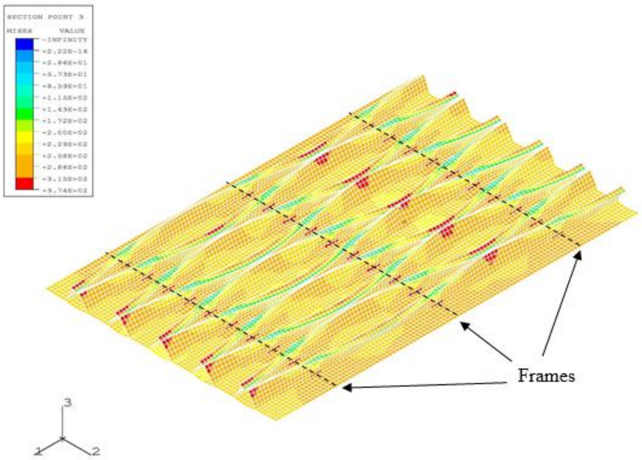

Figure 9. Deformation and stress in bottom panel at collapse. Magnification 10x.

9. Conclusion

Offshore structures consist of continuous panels stiffened by stiffeners and supporting members. Buckling response to FPSO hull stiffened panels of main deck, bottom and inner bottom have been investigated in present paper using the non-linear finite element code ADVANCE/ABAQUS, where both material inelastic effects and non-linear geometric effects have been accounted for. The capacities of the bottom panels have been predicted under simultaneously acting lateral pressure and axial compression. The upper deck was only exposed to axial compression. The capacities of the bottom panels are predicted under simultaneously acting lateral pressure of 0.249 MPa for inner bottom and 0.146 MPa for the bottom and axial compression. For both the bottom and the inner bottom panel the pressure acts from the ballast tank and outward. The upper deck was only exposed to axial compression. The Ultimate Limit State (ULS) capacities have been computed to 260 MPa for the upper deck, 205 MPa for the inner bottom and 250 MPa for the bottom shell.

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