CRITICAL AZIMUTH FOR STABILITY REQUIREMENTS IN DAMAGED CONDITIONS OF RING PONTOON SEMI-SUBMERSIBLE PLATFORMS

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Abstract. *The stability standards for intact and damaged conditions contained in international stability codes and regulations generally do not have an explicit indication of which direction they should be applied. For most ships and floating structures this implicit requirement do not become an issue, since their slender hulls clearly indicates the critical direction, usually the transverse one. But in offshore ring pontoon semi-submersible platforms this is not a straightforward perception considering that the hull main dimensions, length and breadth, are both of similar magnitudes. Besides, in damaged conditions, the critical direction, at first glance, seems to be logically well defined by the static resting position. The results gathered and presented in this paper, however, show that the critical stability azimuths in damaged conditions of these structures are quite different from those expected from the respective static equilibrium positions. This is particularly true when the evaluated damaged criteria do not involve areas (energy) under static stability curves but require minimum values for righting arms in the positive residual stability range after the damage. Therefore, this work points out two very important conclusions. First of all, for floating bodies like semi-submersible platforms the critical stability azimuth in damaged conditions is not the same azimuth of the resting position. And second, this leads to the need of an azimuth sweep to determine the critical direction. Although, so far, it is not yet possible predict in which angles range the critical azimuth should be located for a specific damaged condition, it is clear that it depends on some factors like the hull form (submerged and above the waterline), the existing downflooding points and the hypothetical damage configuration (flooded compartments).*

Keywords*: semi-submersible platforms, damaged stability*

1. INTRODUCTION

In this paper the possibility of misuse of current international regulations, rules and criteria for the evaluation of damaged stability of offshore platforms is addressed, regarding the direction or azimuth they should be applied, because these regulations themselves generally do not contain an explicit indication of it.

After suffering any damage, a floating structure might have some level of survivability, meaning that it can be able to find another resting position of equilibrium. This would be provided if the structure has been designed complying with the adequate stability standards given by the applied regulations. Since the new structure floating position probably will be in an inclined position at some direction, it seems to be natural consider that direction of inclination also as the critical one, no matter the criteria used to assess or predict its static stability behavior. Such assumption looks like a common sense since the structure is resting in a half way or closer to capsizing or sinking.

This work, however, shows that, depending on the kind of stability criteria used, the critical azimuth, apparently well defined by the static equilibrium position, is quite different from it and must be carefully investigated. In other words, the minimum inertia direction is not necessarily the critical one for some stability criteria.

The main subject of this work, therefore, is centered in the need of a search with azimuth variation to determine the critical direction of stability in a damaged condition. The present work does not intend to carry through a complete stability study of case but only prove the necessity of the variation of the azimuth (Freitas, 2009).

2. PLATFORM'S GENERAL DESCRIPTION

The main characteristics of the semi-submersible platform used in this work are listed in Tab. 1. The unit is an oil production semi-submersible floating platform with four columns, four pontoons and four blisters, one in each column.

The stability evaluation done has been divided in the following steps: geometric modeling of the ring pontoon semi-submersible platform; intact stability analysis; verification of the maximum permissible KG (height of center of gravity) at operational draft, considering two compartments in the aft starboard column damaged and as downflooding point the superior extremity of the chain lockers; and, finally, the demonstration that the maximum KG is found in a direction that do not correspond to the static equilibrium azimuth.

The reference coordinate system adopted is illustrated in Fig. 1. The origin of the system is located at the center of the platform at the water level. The X axis is positive aft, the Y axis is positive to starboard and the Z axis is positive upwards, as well the respective coordinates defining the center of buoyancy and center of gravity positions. The azimuth is positive counterclockwise and, then, negative clockwise. Figure 2 shows the hull geometric modeling of the platform obtained with the SSTAB software (Petrobras/Cenpes, 2008).

Table 1 - Main characteristics of the semi-submersible platform

Length Overall	116.0 m
Longitudinal Distance Between Columns' Centers	67.5 m
Breadth Overall	110.0 m
Transverse Distance Between Columns' Centers	67.5 m
Longitudinal Pontoons (2) (Length x Breadth x Depth molded)	50.0 x 17.5 x 12.0 m
Transverse Pontoons (2) (Length x Breadth x Depth molded)	50.0 x 17.5 x 12.0 m
Columns Width (4)	17.5 m
Columns Height (4)	31.3 m
Main Deck Elevation	54.0 m
Cellar Deck Elevation	46.0 m
Bottom Deck Elevation	44.5 m
Spider Deck Elevation	38.5 m
Draught (operational)	275 m
Displacement (operational draught)	80,985.8 t
Draught (transit)	16,5 m
Displacement (transit draught)	65,227.7 t
Draught (repair)	19.3 m
Displacement (repair draught)	69,255.3 t
Draught (survival)	23.0 m
Displacement (survival draught)	74,550.8 t

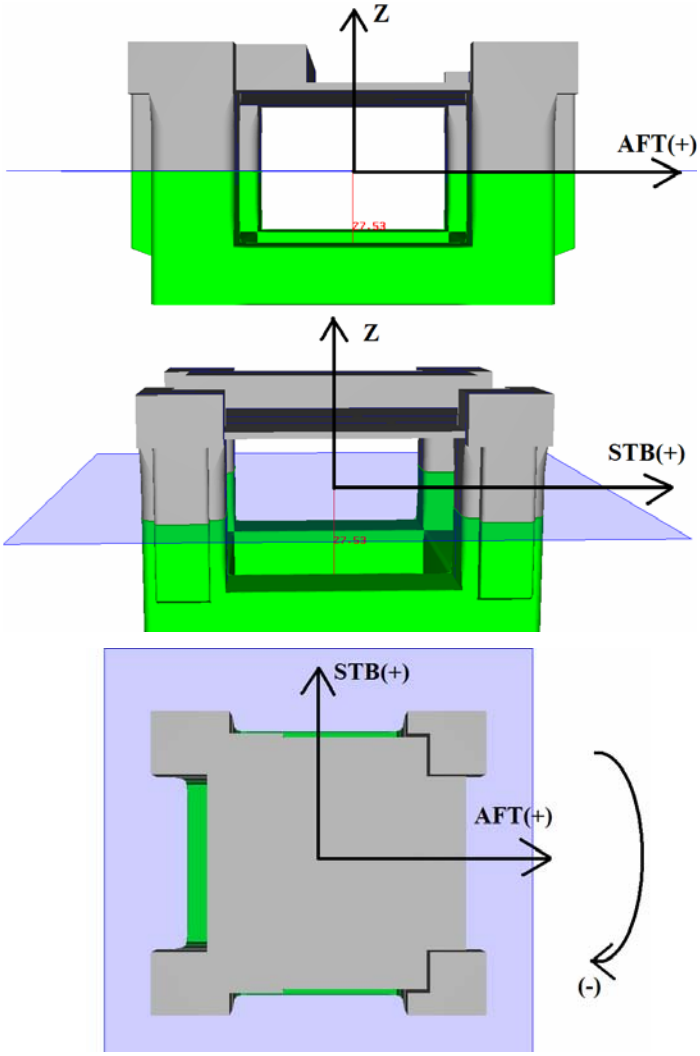


Figure 1 – Coordinate System Adopted

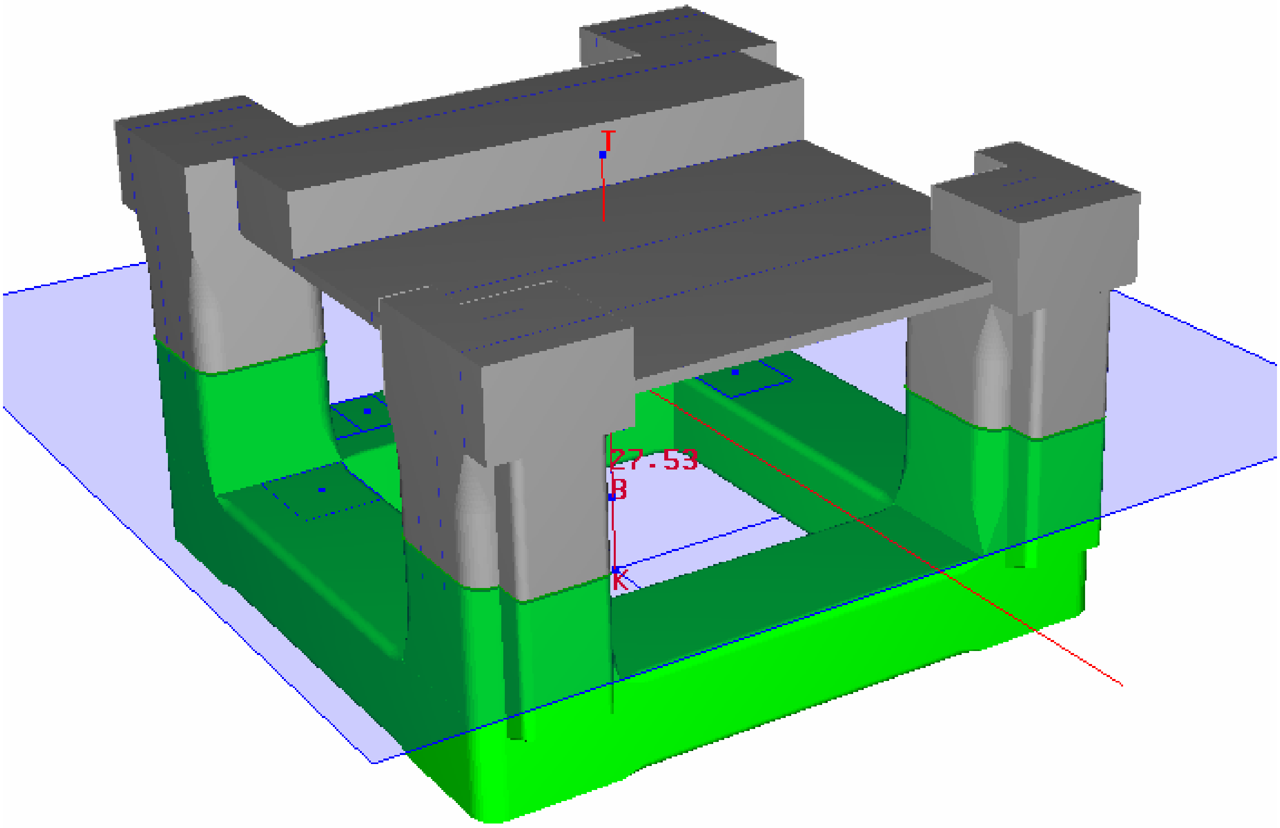


Figure 2 - Hull Modeling

2. INTACT STABILITY ANALYSIS

The determination of the maximum permissible KG for the intact stability condition was performed in an iterative way, starting from an estimated initial value. The stability results were obtained from the SSTAB software (Petrobras/Cenpes, 2008) taking into account the criteria defined in the MODU Code (IMO, 1989). After each program running, the results were analyzed and a new guess was made for the next iteration. Some iterations later, it was noticed that the more restrictive stability criterion was the minimum metacentric height, which should be positive (GM > 0). Table 2 shows the iterations closer to the final result adopted: maximum KG of 30.47m with a residual GM of 0.008m.

Table 2 - Intact Stability Condition - Maximum KG Search Results

Used KG (m)	GM (m)
29.55	0.928
30.40	0.078
30.45	0.028
30.50	<0
30.47	0.008
30.48	<0

The intact stability criteria used in this analysis were those taken from the MODU Code (IMO, 1989) for column-stabilized units and the righting and heeling moment curves are illustrated in Fig. 3:

1 - the area under the righting moment curve to the second intercept with the wind heeling moment curve or to the downflooding angle, whichever is less, should be not less than 30% in excess of the area under the wind heeling moment curve to the same limiting angle; and

2 - the righting moment curve should be positive over the entire range of angles from upright to its second intercept with the wind heeling moment curve, meaning that GM should be also positive.

The heeling moment curve has been obtained considering wind forces on each structural member exposed to the wind calculated by the Eq. (1). The wind velocity used was that intended for normal operation: 36 m/s or 70 knots.

$$F = 0.5 C_s C_H \rho V^2 A \tag{1}$$

where:

F is the wind force in newtons,

C_s is the shape coefficient depending on the shape of the structural member exposed to the wind ,

C_H is the height coefficient depending on the height above sea level of the structural member exposed to the wind,

ρ is the air mass density (1.222kg/m^3),

V is the wind velocity in m/s, and

A is the projected area of all exposed surfaces in either the upright or the heeled condition (m^2).

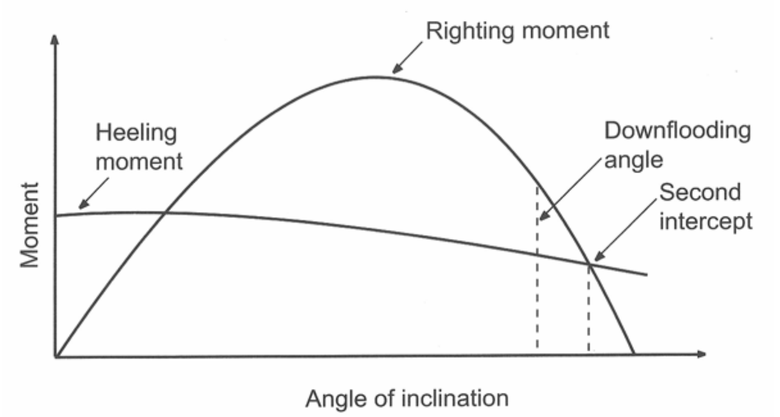


Figure 3 – Righting Moment and Heeling Moment Curves - Intact Stability (IMO, 1989)

The downflooding points considered in the intact stability analysis were chain pipe extremities of the four platform chain lockers and their positions are listed in Tab. 3. The same downflooding points will be used in the damaged stability analysis to determine the extent of weathertight integrity.

Table 3 – Downflooding points location

D. F. Point	X (m)	Y (m)	Z (m)	Column Location
163	39.450	41.475	55.150	Aft Starboard
164	39.450	-41.475	55.150	Aft Port
171	-39.450	-41.475	55.150	Forward Port
172	-39.450	41.475	55.150	Forward Starboard

The next step was to perform a variation of the azimuth for the intact condition, simulating the wind coming from any direction relative to the unit. The azimuth has been systematically varied from 0 to 180 degrees by a step of 15º in both directions, clockwise (-) and counterclockwise (+). The results are presented in Tab. 4.

Table 4 – Maximum KG versus Azimuth for Intact Condition

Azimuth (º)	Max. KG (m)	Min. GM (m)	Azimuth (º)	Max KG (m)	Min. GM (m)
+15	30.47	0.008	-15	30.47	0.008
+30	30.47	0.008	-30	30.47	0.008
+45	30.47	0.008	-45	30.47	0.008
+60	30.47	0.008	-60	30.47	0.008
+75	30.47	0.008	-75	30.47	0.008
+90	30.47	0.008	-90	30.47	0.008
+105	30.47	0.008	-105	30.47	0.008
+120	30.47	0.008	-120	30.47	0.008
+135	30.47	0.008	-135	30.47	0.008
+150	30.47	0.008	-150	30.47	0.008
+165	30.47	0.008	-165	30.47	0.008
+180	30.47	0.008	-180	30.47	0.008

As expected and can be seen in Tab. 4, the azimuth variation has no effect on the resulting maximum permissible KG. Despite the fact that different azimuths can generate different righting and heeling moment curves, the maximum KG will always be limited to the initial stability at the same displacement when we have the positive GM criterion being the determinant one. In other words, the critical azimuth will be associated to the minimum inertia direction.

3. DAMAGED STABILITY ANALYSIS

The damaged stability study has been done considering a set of criteria obtained from three different sources: the MODU Code (IMO, 1989), the Norwegian Maritime Directorate Rules (NMD, 1991) and the Det Norske Veritas Offshore Standard C301 (DNV, 2008). The MODU Code establishes two main conditions to be satisfied after the damage: first, the angle of inclination should not be greater than 17 degrees; and, second, the righting moment curve should have, from the first intercept to the lesser of the extent of weathertight integrity required (downflooding point) and the second intercept between the righting and heeling moment curves, a positive stability range of at least 7 degrees. And, within this range, the righting moment curve should reach a value of at least twice the wind heeling moment curve, both being measured at the same angle. The Fig. 4 illustrates these conditions.

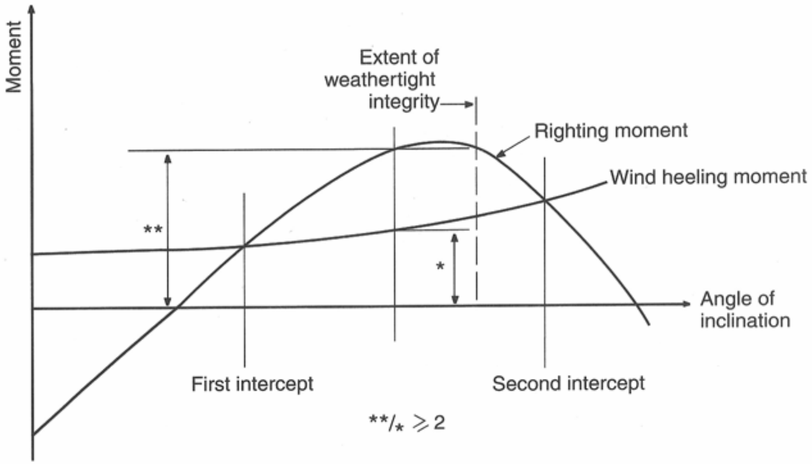


Figure 4 – Righting Moment and Wind Heeling Moment Curves - Damaged Stability (IMO, 1989)

From the NMD Rules only one criterion has been included: the righting moment curve should reach, in the range from the first intercept to the second intercept with the wind heeling moment curve, a value of at least 2.50 meters. This seems to be a robust measure for stability, since platforms satisfying this criterion were capable of resist well to severe storm conditions like those imposed by the Katrina´s hurricane in the Gulf of Mexico. And from the DNV OS-C301 were picked two additional criteria to be considered: the static angle of equilibrium after damage should not be greater than 15 degrees and the area under the righting moment curve should be at least equal to the area under the wind heeling moment curve at the second intercept point between the two curves.

In the damaged condition two compartments in the aft starboard column were flooded and the downflooding points considered were the superior extremities of the chain pipes of the chain lockers, the same downflooding points used in the intact condition. As stated before, only this damaged condition will be analyzed, since the objective here is not find out the ultimate maximum permissible KG of the unit for any condition but demonstrate that it can be found in a different direction from that corresponding to the resting position after the damage. The flooded compartments locations are shown in Fig. 5, as well the other void spaces that could be flooded to generate other damaged conditions.

Finally, the wind velocity considered in the damaged condition was one capable of produce a heeling arm of 0.250m, value obtained from wind tunnel tests for another similar platform. This value corresponds to the effect of a steady wind blowing at 70 knots or 36 meters per second, which is the minimum wind velocity for offshore normal operation service according to the MODU Code rules for this type of platform.

In this stability analysis the results will be obtained considering the righting and heeling moment curves behavior up to the point that the first downflooding should occur. However, as in shown in the NMD rules, it is possible that the criterion of minimum arm can be reached beyond this point, since at higher angles of inclination portions of the platform’s watertight volumes above the initial water level, even above the main deck, can be submerged compensating the losses caused by the flooded spaces and at least partially restoring the righting moment level. But imposing a more restrictive limit do not invalidate the relative and comparative criteria verification made.

Figure 6 shows the equilibrium position reached after the damage under the conditions set before, considering KG equal to 30.47m, the maximum value attained in the intact condition. It occurs at the azimuth value of -16.56°. In this position, at the downflooding angle (28°), the righting arm GZ is equal to 2.124m, below the minimum value of 2.500m required by the NMD rule. Besides, two more criteria used are being violated: the static resting angle (16.94°) is greater than 15° (DNV standard) and the dynamic equilibrium angle (20,08°) is also greater than 17° (IMO standard). Those figures are summarized in Fig. 7 tables and rules checking.

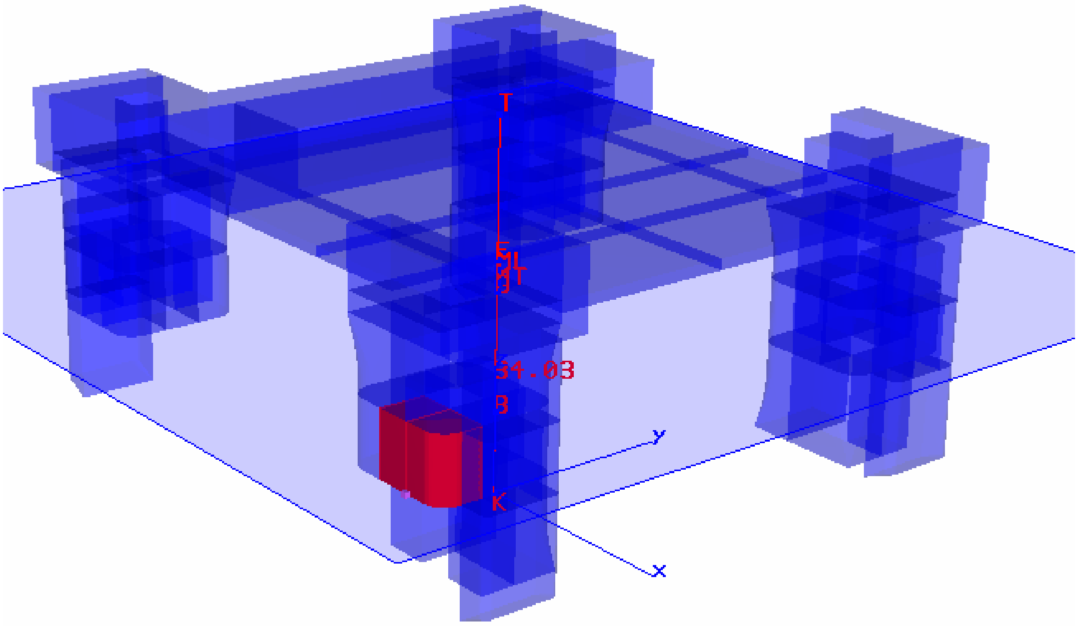
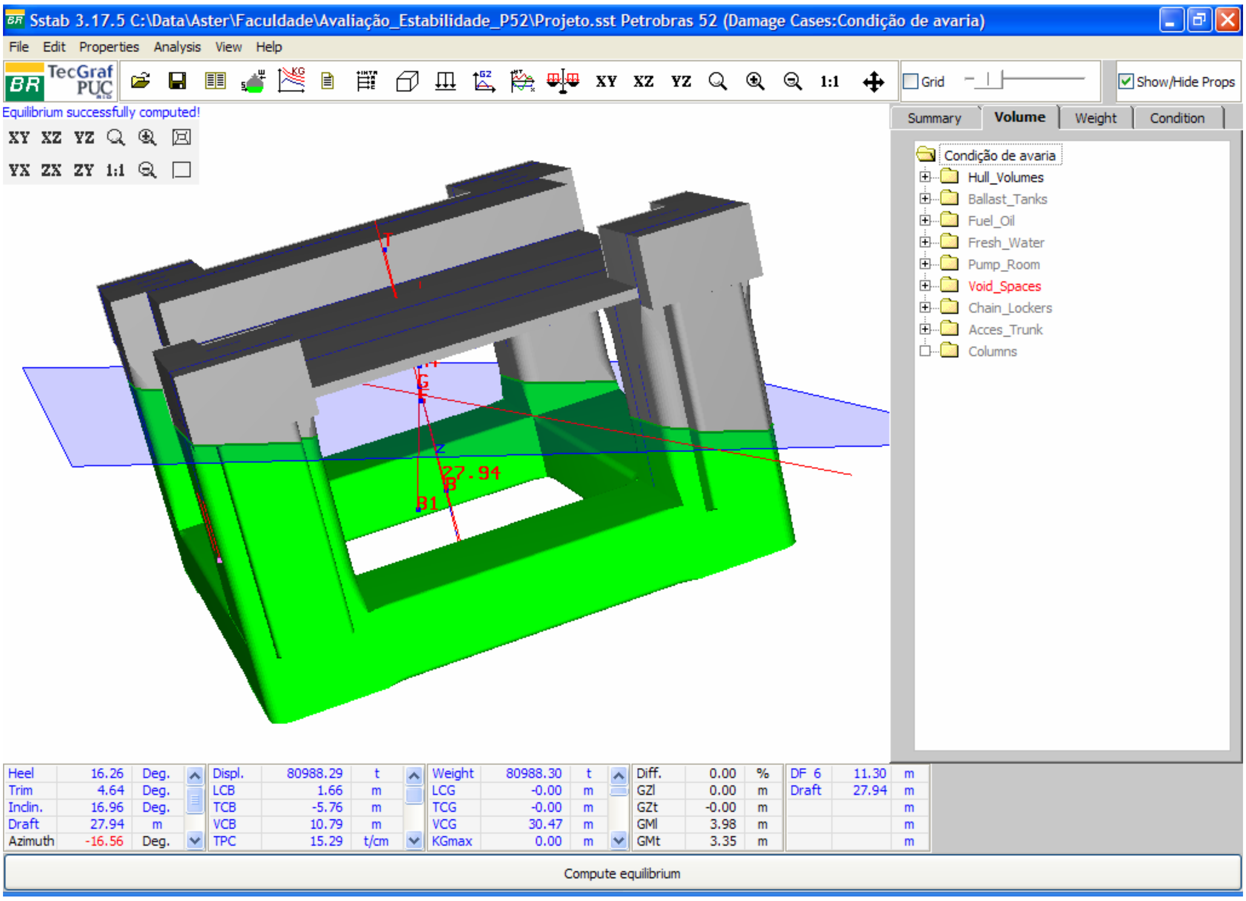


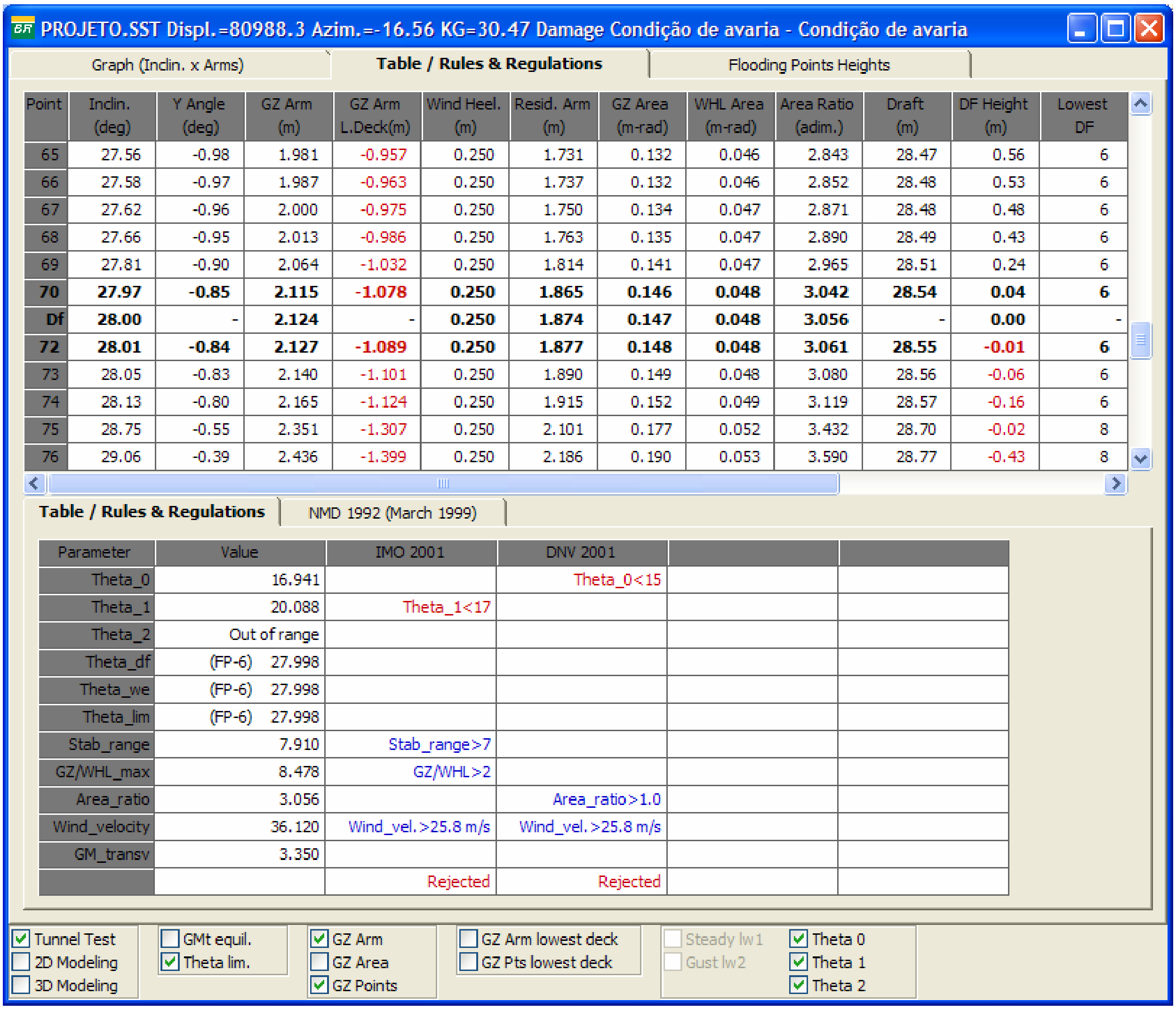
Figure 5 – Void (in blue) and Flooded Compartments (in red) Location in Damaged Condition


Sstab 3.17.5 C:\Data\Aster\Faculdade\Avaliação_Estabilidade_P52\Projeto.sst Petrobras 52 (Damage Cases:Condição de avaria)

Equilibrium successfully computed!

Heel	16.26	Deg.	Displ.	80988.29	t	Weight	80988.30	t	Diff.	0.00	%	DF 6	11.30	m
Trim	4.64	Deg.	LCB	1.66	m	LCG	-0.00	m	GZl	0.00	m	Draft	27.94	m
Inclin.	16.96	Deg.	TCB	-5.76	m	TCG	-0.00	m	GZt	-0.00	m			m
Draft	27.94	m	VCB	10.79	m	VCG	30.47	m	GMl	3.98	m			m
Azimuth	-16.56	Deg.	TPC	15.29	t/cm	KGmax	0.00	m	GMt	3.35	m			m

Figure 6 – Damaged Condition Resting Position for KG = 30.47m



PROJETO.SST Displ.=80988.3 Azim.=-16.56 KG=30.47 Damage Condição de avaria - Condição de avaria

Point	Inclin. (deg)	Y Angle (deg)	GZ Arm (m)	GZ Arm L.Deck(m)	Wind Heel. (m)	Resid. Arm (m)	GZ Area (m-rad)	WHL Area (m-rad)	Area Ratio (adim.)	Draft (m)	DF Height (m)	Lowest DF
65	27.56	-0.98	1.981	-0.957	0.250	1.731	0.132	0.046	2.843	28.47	0.56	6
66	27.58	-0.97	1.987	-0.963	0.250	1.737	0.132	0.046	2.852	28.48	0.53	6
67	27.62	-0.96	2.000	-0.975	0.250	1.750	0.134	0.047	2.871	28.48	0.48	6
68	27.66	-0.95	2.013	-0.986	0.250	1.763	0.135	0.047	2.890	28.49	0.43	6
69	27.81	-0.90	2.064	-1.032	0.250	1.814	0.141	0.047	2.965	28.51	0.24	6
70	**27.97**	**-0.85**	**2.115**	**-1.078**	**0.250**	**1.865**	**0.146**	**0.048**	**3.042**	**28.54**	**0.04**	**6**
Df	**28.00**	-	**2.124**	-	**0.250**	**1.874**	**0.147**	**0.048**	**3.056**	-	**0.00**	-
72	**28.01**	**-0.84**	**2.127**	**-1.089**	**0.250**	**1.877**	**0.148**	**0.048**	**3.061**	**28.55**	**-0.01**	**6**
73	28.05	-0.83	2.140	-1.101	0.250	1.890	0.149	0.048	3.080	28.56	-0.06	6
74	28.13	-0.80	2.165	-1.124	0.250	1.915	0.152	0.049	3.119	28.57	-0.16	6
75	28.75	-0.55	2.351	-1.307	0.250	2.101	0.177	0.052	3.432	28.70	-0.02	8
76	29.06	-0.39	2.436	-1.399	0.250	2.186	0.190	0.053	3.590	28.77	-0.43	8

Parameter	Value	IMO 2001	DNV 2001		
Theta_0	16.941		Theta_0<15		
Theta_1	20.088	Theta_1<17			
Theta_2	Out of range				
Theta_df	(FP-6) 27.998				
Theta_we	(FP-6) 27.998				
Theta_lim	(FP-6) 27.998				
Stab_range	7.910	Stab_range>7			
GZ/WHL_max	8.478	GZ/WHL>2			
Area_ratio	3.056		Area_ratio>1.0		
Wind_velocity	36.120	Wind_vel.>25.8 m/s	Wind_vel.>25.8 m/s		
GM_transv	3.350				
		Rejected	Rejected		

☑ Tunnel Test
☐ 2D Modeling
☐ 3D Modeling
☐ GMt equil.
☑ Theta lim.
☑ GZ Arm
☐ GZ Area
☑ GZ Points
☐ GZ Arm lowest deck
☐ GZ Pts lowest deck
☐ Steady lw1
☐ Gust lw2
☑ Theta 0
☑ Theta 1
☑ Theta 2

Figure 7 – Damaged Position Results and IMO/DNV Rules Checking for KG = 30.47m

However, the resting position after the damage depends on the center of gravity height (KG) considered. So, varying KG will also result in equilibrium positions at different azimuths. Then, the search for the maximum KG will be made in two stages. First, varying the gravity center height to find the highest KG in which all the criteria used are attained, disregarding the azimuth control, leaving the unit reach its resting position naturally at the static equilibrium azimuth. From this point, it will be made a search for a more critical direction, if any, keeping that possible maximum KG constant to demonstrate what the point that is being claimed from the beginning of this work. The results of the first part are presented in Tab. 5.

Table 5 – Maximum Damaged KG Search with Free Azimuth

KG (m)	Azimuth (º)	Max GZ (m)
30.47	-16.56	2.124
30.00	-18.57	2.252
29.50	-20.84	2.388
29.20	-22.23	2.471
29.10	-22.70	2.499
29.09	-22.74	2.500
29.00	-23.15	2.528

During this search, it became clear that the more restrictive criterion was the minimum righting arm of 2.500m required by the NMD rules. That is why, besides KG and azimuth angles, only its values are showed in Tab. 5. Then, the apparent maximum permissible KG seems to be equal to 29.09m at the –22.74º azimuth, as shown in Tab. 5. However, if it would be possible to find another direction which do not comply with the minimum righting arm requirement, for the same KG, this would prove the need for searching the critical azimuth, since it is not the same of the resting damaged condition. Table 6 lists the results obtained for an azimuth sweeping from 0º to -90º with a 10º step, including the original damaged resting position, all of them considering KG constant and equal to 29.09m.

Table 6 – Critical Azimuth Search in Damaged Condition for KG = 20.09m

Azimuth (º)	GZ (m)
0.00	4.290
-10.00	3.370
-20.00	2.600
-22.74	2.500
-30.00	2.320
-35.00	2.240
-38.00	2.210
-39.00	2.200
-39.50	2.196
-40.00	2.194
-50.00	2.420
-60.00	2.650
-70.00	2.880
-80.00	3.900
-90.00	6.030

As can be seen from Tab. 6 above and Fig. 8 below, in this case there is a wide range of azimuth values, at least from -30º to -50º, in which the minimum GZ requirement of 2.500m is not attained. From the same table and figure it is clear that the probable critical azimuth is located around -40º. But this is enough to demonstrate that the critical azimuth does not match the resting position azimuth and the search for this critical direction is mandatory to determine the actual maximum permissible KG of the unit when using minimum righting arms criteria. And it is no necessary to search any further to find out the exact critical azimuth value for this damaged condition nor analyze any other damaged condition to validate these conclusions.

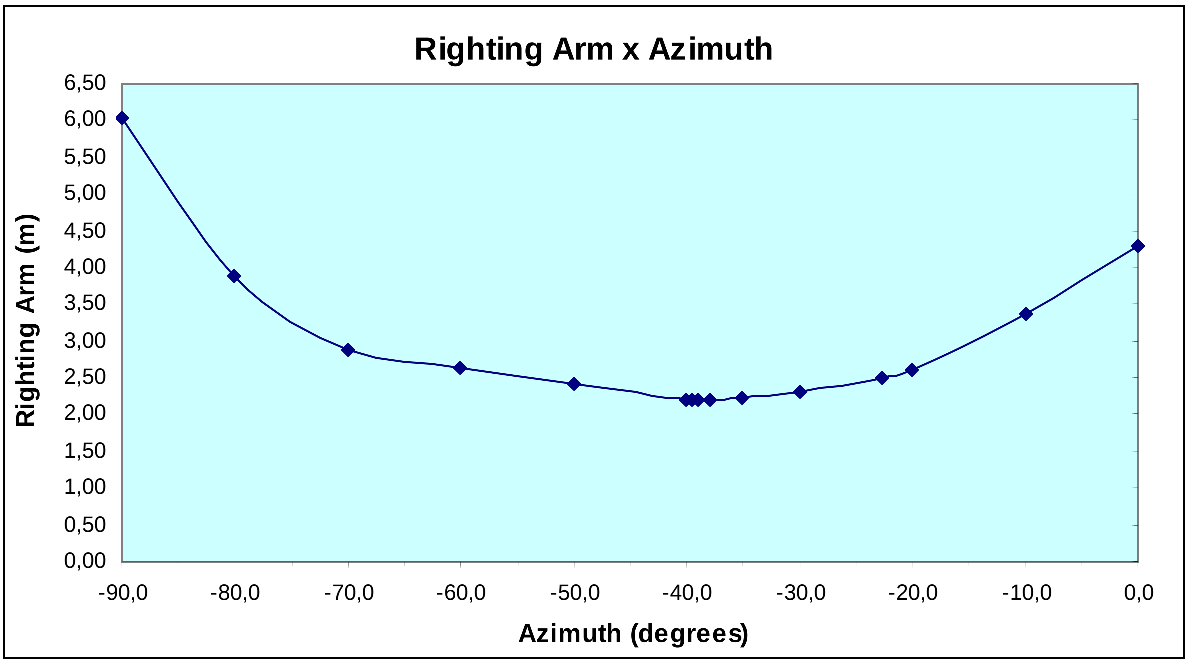


Figure 8 - Maximum Righting Arms versus Azimuth Angles in Damaged Condition for KG = 20.09m

5. CONCLUDING REMARKS

The study carried out in this paper states that, for floating bodies like semi-submersible platforms, the critical stability azimuth in damaged conditions can not be the same azimuth reached in the equilibrium position after the damage. This is particularly true for stability criteria that do not compare energy between the righting and heeling moment curves, like required minimum righting arms absolute values in the residual positive damaged stability range. So, to assure minimum safety levels in a reliable way it is necessary to proceed an exploratory azimuth sweep to determine the maximum KG and the associated critical direction for any damaged condition considered.

The critical azimuth for a specific damaged condition depends on the hull form and the whole structure (submerged, above the water level and even above decks), the location of the downflooding points and the damage configuration analyzed (set of flooded compartments). Although the analysis of only one damaged condition for one platform was sufficient to prove the above statements, it is not enough to establish a standard or means for predicting the location of the critical azimuth. Or, at least, indicating a narrower range it should be within, reducing searching efforts. In fact, there is no certainty that this goal will be eventually reached.

However, this initial research shows that it can be promising and worthy analyze other damaged conditions of the same platform or different ones of the same kind and also put other floating platforms types into the game.

5. ACKNOWLEDGEMENTS

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