STATIC STABILITY OF TENSION LEG PLATFORMS

A Thesis

by

NING XU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2009

Major Subject: Ocean Engineering

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Approved by:

Chair of Committee,	Jun Zhang
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	Ruzong Fan
Head of Department,	David Rosowsky

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ABSTRACT

Static Stability of Tension Leg Platforms. (May 2009)

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Chair of Advisory Committee: Dr. Jun Zhang

The static stability of a Tension Leg Platform (TLP) with an intact tendon system is principally provided by its tendons and hence quite different from those of a conventional ship or even a floating structure positioned by its mooring system. Because small deformations in tendons are capable of providing sufficient righting moment to a TLP, the contribution from the inclination of its hull is relatively insignificant, especially when its tendon system is intact. When the tendon system of a TLP is completely damaged, the static stability of a TLP behaves and is calculated in a similar manner as those of a conventional ship. In the case of a TLP with a partially damaged tendon system, the stability of a TLP may be provided by the deformation of its tendons and to a certain extent the inclination of its hull. Several hurricanes in recent years have raised concerns about the feasibility and the robustness of the TLP concept in the deep water Gulf of Mexico. To the best of our knowledge, existing publications on the research of static stability of TLPs are limited. This study investigates the static stability of different types of TLPs representing those deployed in the Gulf of Mexico, under three different scenarios. That is, a TLP with 1) an intact tendon system, 2) a partially damaged tendon system, and 3) a completely damaged tendon system. The four

different types of TLP chosen for this study are 1) a conventional four-leg TLP, 2) three-leg mini TLP, 3) extended four-leg TLP and 4) mini four-leg TLP. To avoid buckling and yielding occurring in a tendon, we define that the maximum righting moment provided by an intact or partially damaged tendon system is reached when the tension in one or more tendons on the down tension leg becomes zero or when the tension in one or more tendons on the up tension leg starts to yield. This definition leads us to identify the most dangerous (or vulnerable) directions of met-ocean conditions to a TLP with an intact or partially damaged tendon system. Hence, our finding may also be used in the study on the pitch/roll dynamic stability of a TLP. The righting moments of each TLP in the three different scenarios are respectively computed and compared with related wind-induce static upsetting moment at certain velocities. By comparing their ratios, the static stability of a TLP and the redundancy of its tendon system may be revealed, which has important implication to the design of a TLP.

DEDICATION

This is dedicated to my parents, who encouraged me to study in graduate school.

ACKNOWLEDGEMENTS

First of all, I would like to thank Dr. Jun Zhang, chair of my advisory committee, for his guidance and support throughout the course of this research. This thesis would not have been completed if it was not for his help inside and outside the class room. He showed me by example what it takes to become a good academic researcher, and more importantly, to become a responsible individual in the industry and the society as a whole. I would also like to thank Dr. Jeffrey Falzarano and Dr. Ruzong Fan for using their precious time serving as members of my thesis committee. Last but not least, I owe my gratitude to Dr. Richard Mercier, director of the Offshore Technology Research Center, for providing me valuable input information that was needed to conduct this research.

NOMENCLATURE

$\overline{BG}$ = Distance from center of buoyancy to center of gravity

$\overline{BM}$ = Distance from center of buoyancy to metacenter

I_x = Area moment of inertia about X-axis (rolling axis)

N_{total} = Total Number of Tendons on a TLP

T_{yield} = Tension to Yield

ΔT_d = Tension change in a remaining tendon in a damaged tension leg

ΔT_i = Tension change in tendons in the intact leg at the end

ΔT_m = Tension change in tendons in the middle intact leg

∇ = Displacement in volume at a given draft

ABS = American Bureau of Shipping

API = American Petroleum Institute

At = Cross sectional area of a single tendon

Aw = Water plane area of the hull

D = Column Diameter

D = Water Depth

GOM = Gulf of Mexico

GZ = Righting arm

H = Column Height

h = Pontoon Height

HM = Heeling moment

L = Effective Pontoon Length

Loa = Length Overall

N = Number of Damaged Tendons on a TLP

R = Column Radius for four-leg TLPs (or Pontoon radius for SeaStar TLP)

RM = Righting moment

SC = Spare Capacity

SCR = Steel Catenary Riser

Ta = Averaged tension per remaining tendon under damaged condition

TIP = Tension Increase Percentage

To = Pretension per tendon under intact condition

TRM = Total Righting Moment

TRP = Tension Reduction Percentage

TTR = Top Tensioned Riser

TUF = Tendon Utilization Factor

VCG or KG = Input Vertical Center of Gravity with respect to keel

w = Pontoon Width

η = Shift in VCB due to heel

ξ = Shift in TCB due to heel

Φ = Angle of Inclination

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CHAPTER I

INTRODUCTION

Background of Tension Leg Platforms

Of the many deepwater floating platform concepts developed in the past two decades, the Tension Leg Platform (TLP) has been frequently selected when it comes to deepwater oil extraction and production (Kibbee and Snell, 2002). The tendon system of a TLP restrains motions of the platform in response to wind, wave and current to within specified limits. The legs of the system, composed of an array of tendons, connect points on the platform to anchor points on a seafloor foundation. By restraining the platform at a draft deeper than that required to displace its weight, the tendons are ideally under a continuous tensile load that provides a horizontal restoring force when the platform is displaced laterally from its still water position (API, 1997). The hull of a TLP can be described as a "column-stabilized" floating structure, much like the semisubmersible drill rigs from which it derives. Because the TLP design diminishes the wave-induced forces in the tension legs, the proportion of displacement embodied in the columns of the TLP will be a larger fraction of total displacement than for the semisubmersible, whose heave motion response is tailored by having relatively large pontoons which increase the added mass and favorably increase the natural period of heave motions (ABS, 2001).

This thesis follows the style and format of Ocean Engineering.

The TLP technology, like its competitors, semisubmersible and spar, has proven to be reliable and cost efficient. One of the main advantages of the TLP concept is its stability in vertical modes, namely heave, pitch and roll. In these three modes, a TLP has very limited motion and a relatively high natural frequency, as opposed to the much larger and slower vertical motions of semisubmersible and spar. This advantage makes dry tree Top-Tensioned Risers (TTR) and Steel Catenary Risers (SCR) suitable alternatives for oil and gas extraction. Dry completion by means of a surface wellhead platform is a viable alternative to subsea wet completion in all water depths. It offers the benefits of better reservoir testing and monitoring, drilling and workover capabilities, lower operating costs due to ease of well intervention, better flow assurance, as well as increased recovery of oil and gas (Huang, Bhat, Luo et al., 2000).

Over the past decades, several TLP concepts have been developed and used in the Gulf of Mexico (GOM) and elsewhere in the world. A conventional four-leg TLP (referred to as C-TLP) consists of four columns connected by a ring pontoon at the base and a rectangular deck at the top. The extended four-leg TLP (referred to as E-TLP) hull concept developed by ABB Ltd. incorporates a radial pontoon extension at the bottom of each column to support two tendon porches. The extensions effectively increase the restoring effect of the tendons while reducing the column spacing. This reduces the deck span between columns and thereby captures a saving in deck steel weight (Murray, Yang, Yang et al., 2008). The MOSES four-leg mini TLP (referred to as Moses TLP) hull concept developed by MODEC International LLC. has columns with smaller cross-sectional area but more concentrated toward the center of the platform. Each column incorporates a large radial hull extension at its base to support two tendon porches. The SeaStar three-leg mini TLP (referred to as SeaStar TLP) hull concept developed by Atlantia Offshore Ltd. concentrates the column buoyancy in a single large column at the center and incorporates three large radial hull extensions at its base, each supporting two tendon porches. The SeaStar TLP concept has several advantages over four-leg TLPs. It has relatively high hull efficiency (i.e. payload divided by hull weight) and single surface-piercing column allows independent design and optimization for the hull and deck (Kibbee, Chianis, Davies et al., 1994).

Research Objective

Several hurricanes in recent years have raised concerns about the feasibility and the robustness of the TLP concept in the deep water GOM. To the best of our knowledge, existing publications on the research of static stability of TLPs are limited. The primary objective of this research is to investigate the static stability of the aforementioned four types of TLPs with intact, partially damaged and completely damaged tendon systems under extreme hurricanes conditions in the GOM. To avoid buckling or yielding in a tendon, we define that the maximum righting moment provided by an intact or partially damaged tendon system is reached when the tension in one or several tendons becomes zero or reaches its yield capacity. This definition leads us to identify the most dangerous (or vulnerable) directions of met-ocean conditions to a TLP with an intact or partially damaged tendon system. The righting moments of each TLP in the three different scenarios are respectively computed and compared with related wind-induce static upsetting moment at 100-year wind velocities. By comparing their ratios, the static stability of a TLP and redundancy of its tendon system may be revealed, which has important implication to the design of a TLP.

Computational Tools

Static stability analyses in this research were performed for various damaged cases using the commercial software StabCAD. StabCAD is a general purpose interactive, graphics-oriented program for designing and analyzing the stability of all aspects of floating bodies. Regular ship-shaped hulls, unusual configurations, and non-symmetrical geometry can be accurately modeled (Zentech, 1999). The stability module was designed to perform stability analysis, including calculation of hydrostatic parameters, cross curves of stability, righting arms, wind heeling arms, intact and damage stability parameters and calculation of tank capacity tables. Data input was performed using the interactive graphics generator and preprocessor module PreStab with the help of the spreadsheet style editor BETA.

Tension Righting Moments and Tension Reduction Percentage and Tension Increase Percentage were calculated based on Hooke's law, assuming the hull is rigid and the tendons elongate or shorten when the hull is inclined. MatLab is used for these calculations.

CHAPTER II

CHARACTERISTICS OF FOUR TLPS

Main Particulars

Because some data related to existing TLPs are proprietary, main dimensions of the TLPs chosen for our study were collected from the internet or related papers that disclosed either the exact or very closely resembled numbers used in the design. In StabCAD calculations, buoyancy of the deck and other topside superstructures (e.g. drilling derrick) is not considered when they were submerged at large angle of inclination, due to lack of sufficient topside information. All panels and cylinders in the model are subject to wind load should they emerge out of water. Table 1 lists the main particulars of the TLPs selected for this study.

Table 1. Main particulars

	C-TLP	SeaStar TLP	E-TLP	Moses TLP
Modeled After	Brutus	Morpeth	Magnolia	Marco Polo
Length Overall [m]	80	52.7	65.2	105
Pontoon Size L x W x H [m]	46 x 15 x 5	26.9 x 6.8(4.8) x 7.6	34 x 8.4 x 6.8	23.2 x 23.2 x 14.5
Pontoon Extension Size L x W x H [m]	N/A	35.1 in Radius	7 x 7 x 7	31.7 x 6.6 x 14.5(6.6)
Column Size [m]	20 dia. x 51 H	17.7 dia. x 34.1 H	17.5 dia. x 39.5 H	9.2 L x 6.6 W x 60 H
Deck Dimensions L x W x H [m]	80 x 80 x35	33.5 x 33.5 x 13	68 x 68 x 12	56.6 x 56.6 x 20
Payload (topside, risers, etc.) [mt]	19958	3178	13816	12973
Hull Weight [mt]	13154	2497	10000	5216
Total Displacement [mt]	49623	10624	34287	24873
Pretension [mt]	16511	4949	10471	6684
Pretension Per Tendon [mt]	1376	825	1309	836
Assumed KG [m]	27.5	27.7	25.3	39.7
Tendon Outer / Inner Diameters [mm]	813 / 781.3	660.4 / 635.0	813 / 781.3	711.2 / 680.72
Tendon Young's Modulus [Mpa]	2.0E+05	2.0E+05	2.0E+05	2.0E+05
Assumed Tendon yield strength [Mpa]	8.00E+02	8.00E+02	8.00E+02	8.00E+02
Tendon stiffness (k) [N/m]	9.00E+06	1.05E+07	5.67E+06	5.24E+06
Number of Tendons Per Tension Leg	3	2	2	2
Water Depth [m]	910	518.3	1425	1311
Operating Draft [m]	27.5	27.7	25.3	39.7

Models

The four TLPs chosen in our study are depicted in Figures 1 through 4. To simplify the modeling process, the square pontoon extensions of the E-TLP were modeled as cylinders of the same volume, as seen in Figure 3. This change will not affect hydrostatic properties of the hull.

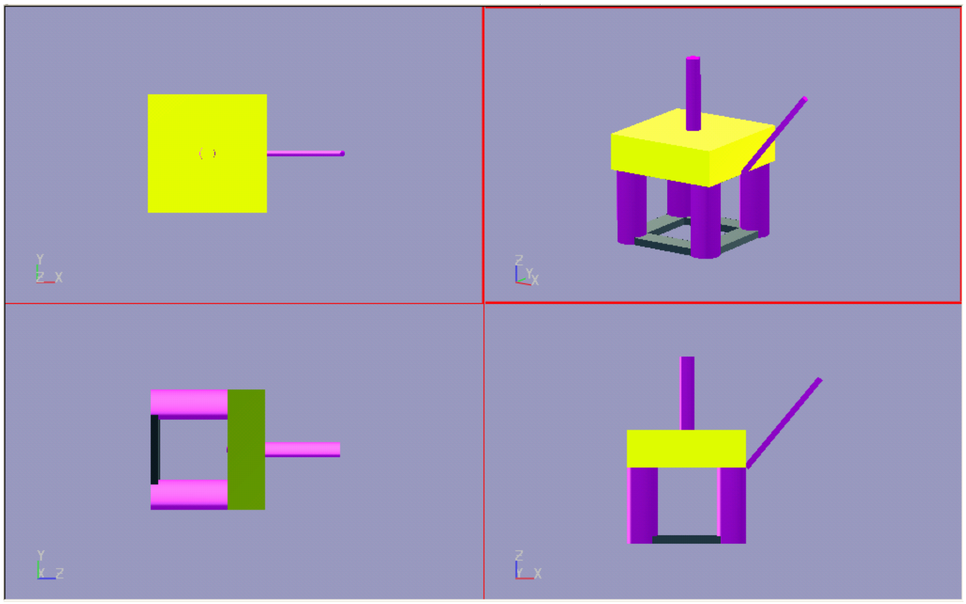


Figure 1. C-TLP model in StabCAD

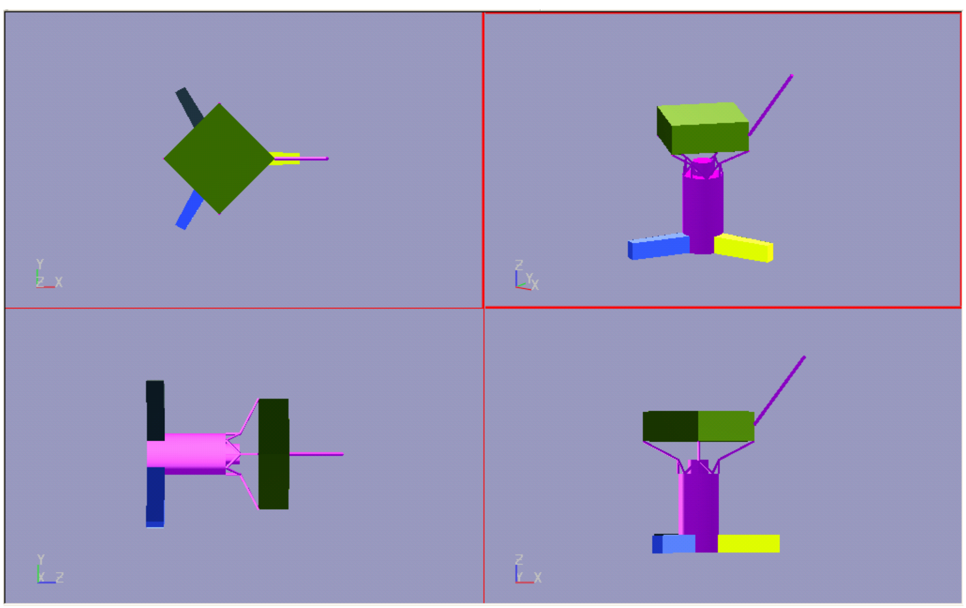


Figure 2. SeaStar TLP model in StabCAD

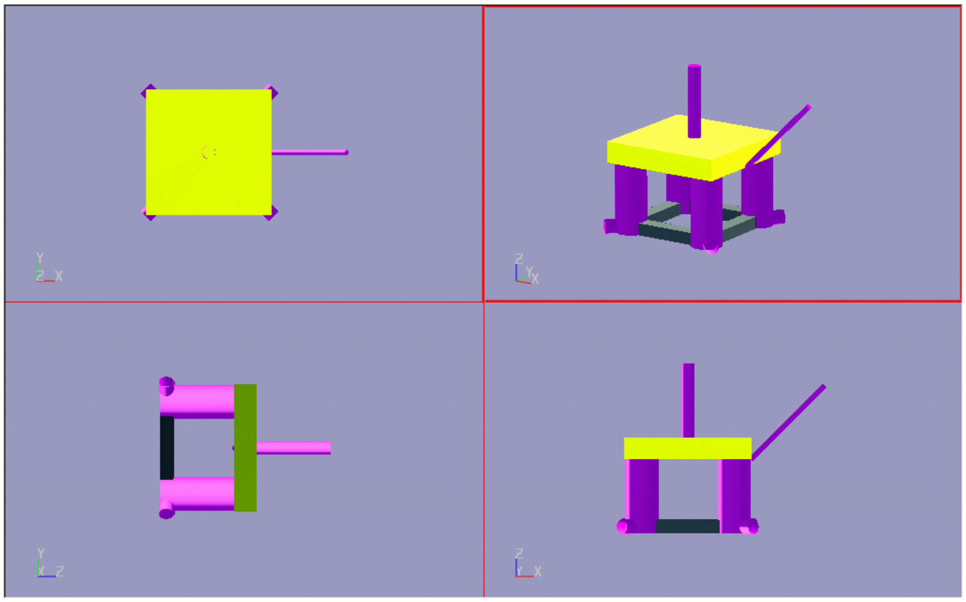


Figure 3. E-TLP model in StabCAD

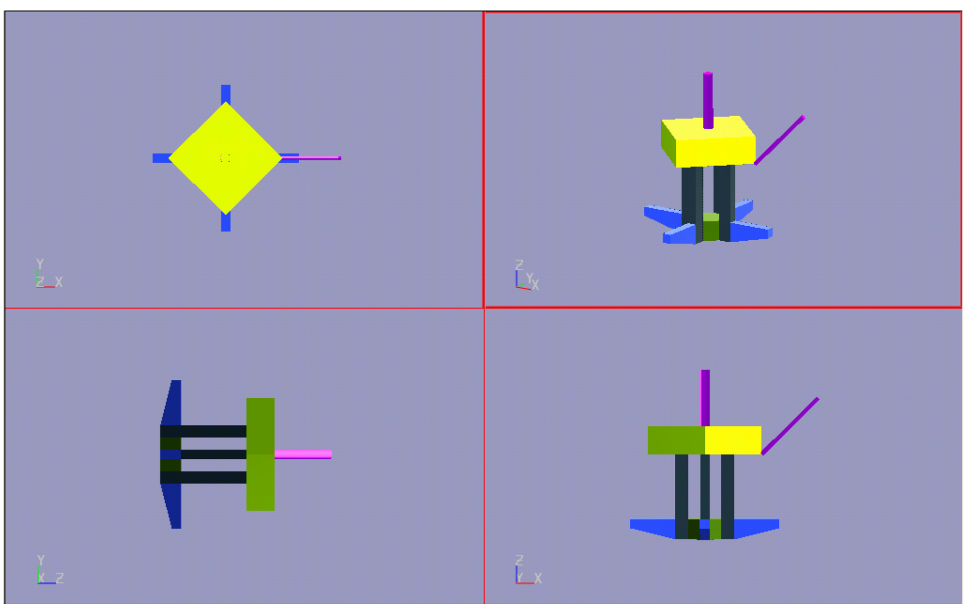


Figure 4. Moses TLP model in StabCAD

CHAPTER III

STABILITY WITH INTACT OR PARTIALLY DAMAGED TENDONS

Assumptions and Approximations

Several assumptions and approximations made in this study are described in this section. When the TLP is inclined due to an upsetting moment, we assume that the hull is rigid and will not deform while the tendons may shorten or elongate. The connections between tendons and hull are of hinge type. Buckling of tendons on the down tension leg and yielding of tendons on the up tension leg are considered as the two governing criteria of tendon failure during pitch/roll. Damaged tendons due to buckling or yielding are assumed to be disconnected (i.e. completely separated at tendon porch) from the hull for simplification. During their deformation, the tendons' behavior follows Hooke's Law, thus has a linear stress-strain relationship. Young's modulus and yield strength of the tendon tubes are assumed to be 2.0×10^5 MPa and 800 Mpa, respectively (MatWeb, 2009). Due to lack of information provided by the related companies, the vertical center of gravities (VCG) of all four TLPs are assumed to be at the still waterline, making the KG value equal to the corresponding operating draft. When the tendon system of a TLP is intact or partially damaged, the angle of inclination of the hull is usually very small (i.e. much less than $5°$), hence the approximation $\sin \phi \cong \phi$ is used in our computation for the total righting moments. Wave and current induced moments are not studied here.

Stability of C-TLP with Intact and Partially Damaged Tendon System

Two major rolling cases were considered for analyzing the intact stability of the C-TLP, as shown in Figure 5:

1. Strict tilt: rolling axis is coincident with one of the hull's 'longitudinal' axes
2. Diagonal tilt: rolling axis is parallel or coincident with one of the diagonals of the hull

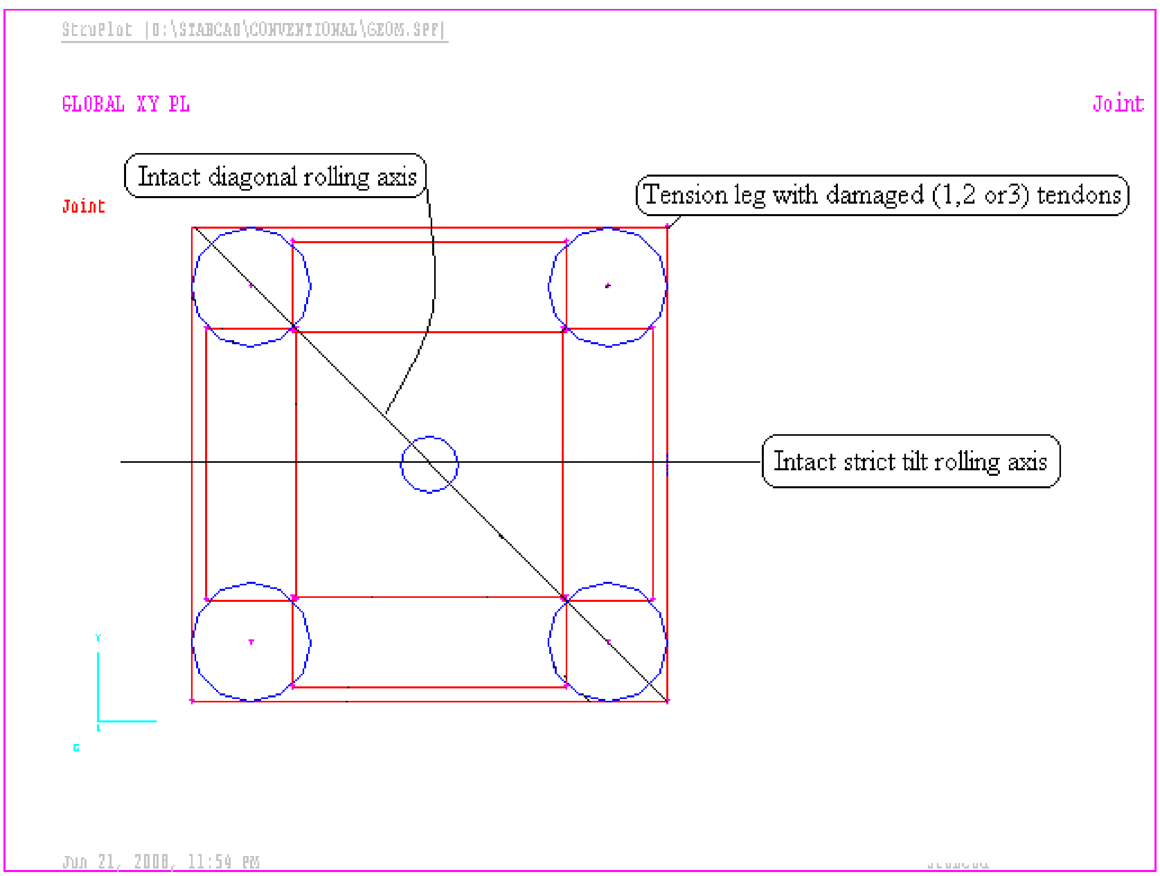


Figure 5. Rolling axis definition

Righting Moment in Strict Tilt

When the C-TLP rolls with respect to its longitudinal axis, the righting moment is named as strict tilt righting moment for the purpose of description. Following Hooke's Law, the stress-strain relationship of a steel tendon is given by,

$$E = \frac{\sigma}{\epsilon} \tag{1}$$

Based on the definition of strain, $\varepsilon = \frac{\Delta L}{L}$ and stress, $\sigma = \frac{F}{A}$, the additional tension applied to a tendon is related to the additional elongation through Equation (2)

$$\Delta T = \frac{E A_t \Delta L}{L} \tag{2}$$

where $A_t = \frac{\pi}{4}(D_{out}^2 - D_{in}^2)$ represents the cross sectional area of a single tendon and D_{out} and D_{in} are the outer and inner diameter of the tendon tube, respectively. Tendon length L is equal to the water depth subtracting the operational draft. Since $\frac{E A_t}{L}$ of a given TLP system is constant, we define it as the stiffness constant *k*, therefore

$$\Delta T = k \Delta L \tag{3}$$

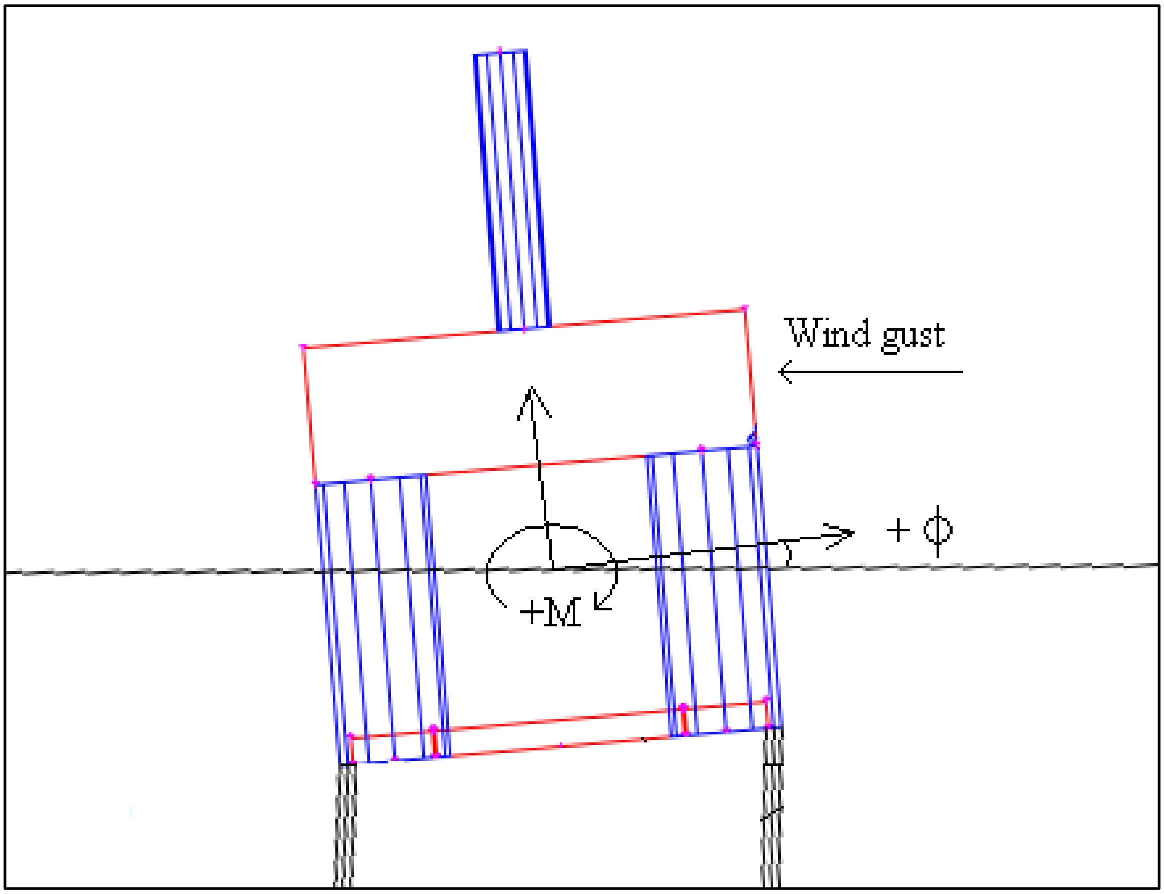


Figure 6. Sign convention

As shown in Figure 6, the hull inclination angle ϕ, is defined as positive when the body rotation is in the same direction as the wind upsetting moment. As a result, a positive righting moment going in the opposite direction is provided by the tendons and the shift in center of buoyancy. The damaged tendons are assumed to be on the right side of the hull, without loss of generality. Wind can be blowing from either side of the hull. In later text, it should be noted that "damaged leg up" means that the wind is blowing from the side with damaged tendon(s), as illustrated above. On the other hand, "damaged leg down" means that the wind is blowing from the side with intact tendons.

When the tendon system is intact, the tension change in a tendon under strict tilt condition is given by,

$$\Delta T = k\left(\frac{Loa}{2}\phi\right) \tag{4}$$

where Loa stands for Length Overall of the hull (i.e. the longitudinal end to end length). Hence, strict tilt righting moment exerted on the C-TLP by intact tendons can be calculated by

$$M = [6(T_o + \Delta T) - 6(T_o - \Delta T)]\left(\frac{Loa}{2}\right) \tag{5}$$

or simply

$$M = 3(Loa^2)k\phi$$

where T_o is the pretension of a single tendon under intact condition, which is equal to $(B - W)/12$ for the C-TLP.

Righting Moment in Diagonal Inclination

The other case we considered, shown in Figure 5, is when the rolling axis is oriented diagonally from one corner to its opposite corner of the C-TLP. Later we will focus only on the diagonal rolling case for the C-TLP because the diagonal inclination case is the most vulnerable case for the buckling and yielding of tendons. In fact, for all four-leg TLPs of a square shape pontoon, righting moment provided by an intact tendon system is independent of the rolling axis' orientation as long as the axis passes through the center of the square. However, due to a longer tendon-to-axis distance (moment arm), diagonal inclination results in larger reduction in tension of tendons and hence is the most vulnerable case. This concept will be explained later in Chapter V and mathematically proved in Appendix A.

Two cases are considered for diagonal inclination for a C-TLP with a partially damaged tendon system:

1. Damaged tension leg up: leg with 1, 2 or 3 damaged tendons moving upward
2. Damaged tension leg down: leg with 1,2 or 3 damaged tendons moving downward

In cases of a TLP with partially damaged tendons, the hull's rolling axis shifts horizontally from and in parallel with the original diagonal line toward the leg at the opposite corner to the leg with damaged tendons, as shown in Figure 7.

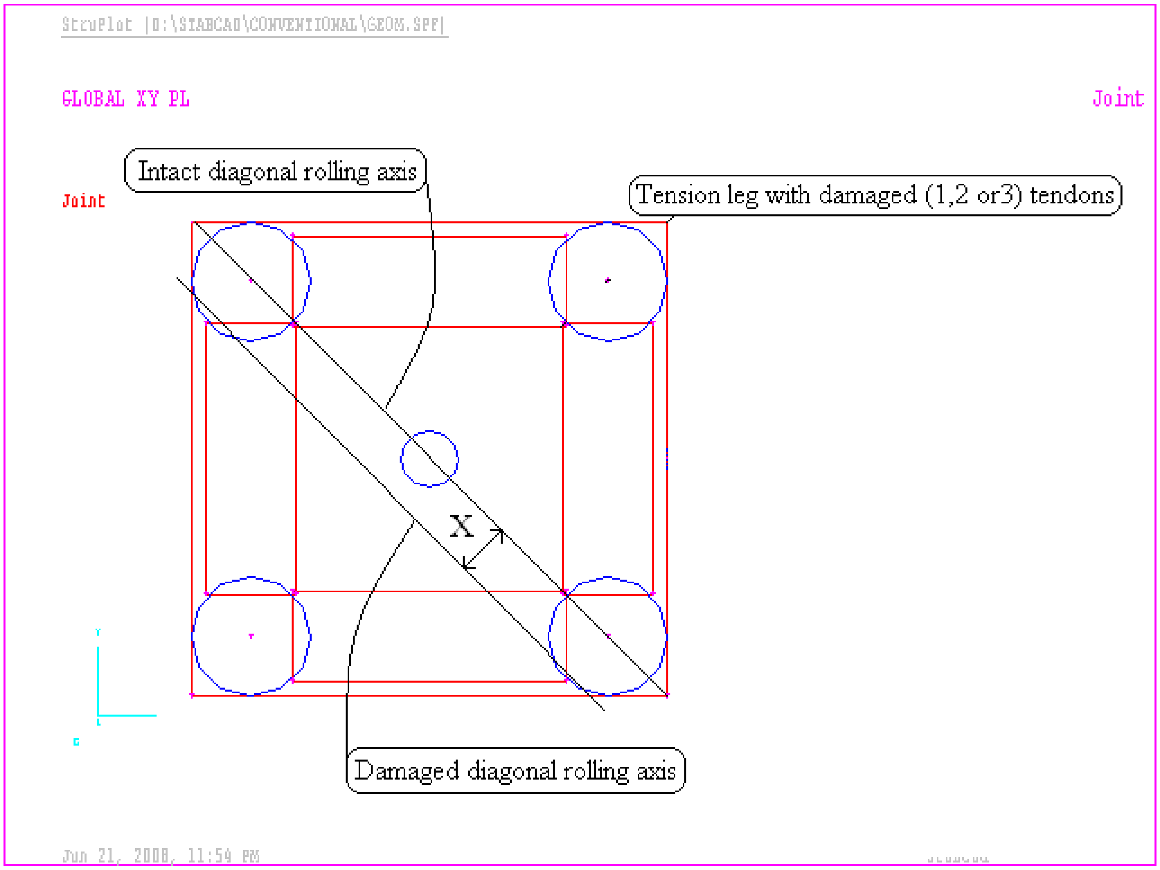


Figure 7. Shifting of diagonal rolling axis of C-TLP

The offset, x, can be determined based on the fact that the total vertical force of the remaining tendons is balanced by the difference between the buoyancy and weight of the hull. For generality, number of damaged tendons on a leg is denoted as N. T_a is defined as the averaged tension of remaining tendons and ΔB is the buoyancy decrease due to the loss of N tendons. The derivation of the solutions for T_a and ΔB will be presented in the following section. In the case that tendon system is intact, $N = 0$ and $T_a = T_0$. Hence, the intact tendon system can be viewed and will be treated as a special case of the partially damaged tendon system from this chapter on.

The total vertical force applied on the C-TLP is balanced based on the equilibrium condition, which leads to,

$$(3-N)(T_a+\Delta T_d)+6(T_a+\Delta T_m)+3(T_a-\Delta T_i)=B-\Delta B-W \quad N = 0,1,2,3 \tag{6}$$

where by definition

$$T_a=\frac{B-\Delta B-W}{12-N}\,, \tag{7}$$

$$\Delta T_d=k\left(\frac{Loa}{\sqrt{2}}+x\right)\phi\,, \tag{8}$$

$$\Delta T_m=kx\phi\,, \tag{9}$$

$$\Delta T_i=k\left(\frac{Loa}{\sqrt{2}}-x\right)\phi\,. \tag{10}$$

ΔT_d, ΔT_m and ΔT_i are the tension change in each remaining tendon on the leg of N damaged tendons, tension change in each tendon on the middle intact leg and tension change in each tendon on the intact leg at the opposite corner of the leg of N damaged tendons, respectively.

Substitute Equations (7), (8), (9) and (10) into Equation (6), we obtain

$$(3-N)\left(\frac{Loa}{\sqrt{2}}+x\right)+6x-3\left(\frac{Loa}{\sqrt{2}}-x\right)=0 \quad N=0,1,2,3 \tag{11}$$

Equation (11) leads to

$$x=\left(\frac{N}{12-N}\right)\frac{Loa}{\sqrt{2}} \quad for\ N=0,1,2,3 \tag{12}$$

Buoyancy and Tension Adjustment

The pretension of a TLP is obtained by subtracting its total weight from its buoyancy when the tendon system is intact. When one or more tendons are damaged, tensions in each of the remaining tendons increase in general. Elongation of these tendons caused by the increase in tension slightly reduces the draft and causes the buoyancy to decrease. Due to the decrease in buoyancy, there is a slight tension decrease in each remaining tendon consequently. Instead of using an iterative procedure, a vertical force equilibrium equation and Hooke's law, Equation (13), are used to analytically solve for the Buoyancy decrease, ΔB, and the averaged tension per tendon, T_a. N_{total} stands for the total number of tendons when the tendon system is intact (e.g. for C-TLP, $N_{total} = 12$), ΔL is the average elongation due to increase in tension, and A_w is the water plane area of the hull at the draft. It should be noted the following derivation is valid for all types of TLPs.

$$\begin{cases} (N_{total} - N)T_a = B - \Delta B - W \\ T_a = k\Delta L + T_o \end{cases} \quad for\ N = 0,1,2,3 \tag{13}$$

where

$$T_o = \frac{B - W}{N_{total}},$$

$$\Delta L = \frac{\Delta B}{\rho g A_w}.$$

Solving Equation (13) we get Equations (14) and (15),

$$\Delta B = \frac{N T_o}{\frac{(N_{total} - N)k}{\rho g A_w} + 1} \quad for\ N = 0,1,2,3 \tag{14}$$

$$T_a = \frac{k}{\rho g A_w}\Delta B + T_o \tag{15}$$

Knowing the location of the rolling axis along with buoyancy and tension adjustments for intact and partially damaged cases, we can now determine the change of tension of each tendon due to the inclination of the hull and then calculate the righting moment when the hull is diagonally inclined at an angle ϕ.

For conventional ships or other freely floating structures, righting moment provided by buoyancy at a given angle of inclination are expressed in term of righting arm, GZ, which is equal to the righting moment divided by the displacement. In cases of partially damaged TLPs where there are remaining tendons pulling down on the hull, majority of the righting moment is still provided by the tendon system.

Total Righting Moment (TRM) can be expressed as the sum of righting moments contributed by tension variation in tendons and those by the buoyancy and weight of the hull.

$$TRM = RM_T + RM_B \tag{16}$$

The first term in Equation (16), RM_T, is the righting moment contributed from the combination of elongation and shortening of tendons resulted from the inclination of the hull, which accounts for majority of the righting moment. Taking the total moment provided by the tendons with respect to the original diagonal axis of the topside of the hull, we get Equation (17).

$$RM_T = \begin{cases} (3-N)(T_a+\Delta T_d)\left(\frac{Loa}{\sqrt{2}}\right) - 3(T_a-\Delta T_i)\left(\frac{Loa}{\sqrt{2}}\right) & Damaged\ leg\ up \\ 3(T_a+\Delta T_i)\left(\frac{Loa}{\sqrt{2}}\right) - (3-N)(T_a-\Delta T_d)\left(\frac{Loa}{\sqrt{2}}\right) & Damaged\ leg\ down \end{cases} \tag{17}$$

$$N = 0,1,2,3$$

or simply

$$RM_T = [3\Delta T_i + (3-N)\Delta T_d \pm NT_a]\left(\frac{Loa}{\sqrt{2}}\right) \quad N = 0,1,2,3$$

where again defined in Equations (8) and (10)

$$\Delta T_d = k\left(\frac{Loa}{\sqrt{2}} + x\right)\phi\ ,$$

$$\Delta T_i = k\left(\frac{Loa}{\sqrt{2}} - x\right)\phi\ .$$

The TRM of a C-TLP can be simplified as

$$TRM = C_1 + (C_{2t} + C_{2b})\phi \tag{18}$$

where C_1 is a constant ($C_1 < 0$ when damaged leg up and $C_1 > 0$ when damaged leg down) which represents the sum of all the non ϕ terms in RM_T, and C_{2t} is a positive constant representing the sum of all the ϕ terms in RM_T and C_{2b} is a constant representing the sum of all the ϕ terms in RM_B, which will be introduced soon. The sum of these two constants governs the linear rate of increase of TRM as a function of ϕ.

Setting TRM equal to zero, we are able to determine the initial angle of inclination, ϕ_{ini}, at equilibrium (zero moment) for a TLP with a partially damaged tendon system. Equation (18) is then simplified to an even more straight forward form,

$$TRM = (C_{2t} + C_{2b})(\phi - \phi_{ini}) \quad where\ \phi_{ini} = -\frac{C_1}{C_{2t} + C_{2b}} \tag{19}$$

The magnitude of ϕ_{ini} stays constant for one damage case ($\phi_{ini} > 0$ when damaged leg up and $\phi_{ini} < 0$ when damaged leg down).

The second term in Equation (16), RM_B, is the righting moment contributed from the combination of the buoyancy and weight of the hull. It should be noted the buoyancy, *B*, for the C-TLP is 4.87×10^8 N. On the other hand, buoyancy decrease, ΔB, when N = 3, is only 5.49×10^6 N, about one hundredth of the original buoyancy. Hence ΔB is much smaller than B in magnitude. The percentage of buoyancy decrease for all TLPs and damage cases will be tabulated in Chapter V. Since the inclination angle is expected to be small, RM_B is calculated using the formula based on the assumption of small angle inclination.

$$RM_B = \overline{BM}\phi(B - \Delta B) - \overline{BG}\phi W \quad N = 0,1,2,... \tag{20}$$

where $\overline{BM}$ is the vertical distance from center of buoyancy to metacenter and $\overline{BG}$ is the vertical distance from the center of buoyancy to center of gravity.

To calculate the Tension Reduction Percentage (TRP) of the tendons on the down tension leg, Equation (21) is used.

$$TRP = \frac{\Delta T_{lower}}{T_a} \times 100\% \tag{21}$$

ΔT_{lower} is ΔT_i in the damaged leg up case and ΔT_{lower} is ΔT_d in the damaged leg down case. Tendons on the down tension leg will start to buckle when TRP reaches 100%.

Yield check on each tendon was also performed. We assume the yield strength, σ_y, of the steel tubes used by the tendons of all four TLPs to be 800 MPa. Thus the yield tension for a given tendon is

$$T_{yield} = \sigma_y \times A_t \tag{22}$$

The Tendon Utilization Factor (*TUF*) of tendons on the up tension leg is defined by

$$TUF = \frac{T_a(1 + TIP)}{T_{yield}} \tag{23}$$

where Tension Increase Percentage (*TIP*) is the percentage of the tension increase in the tendons on the up leg(s) of the hull and has the same value as the *TRP*. *TUF* reaches 1.0 when the tension in a tendon reaches its yielding strength. Therefore we define the allowed TIP of any tendon under a certain intact or damaged condition as

$$TIP_{allowed} = \left(\frac{T_{yield}}{T_a} - 1\right) \times 100\% \tag{24}$$

Tendons on the up tension leg will start to yield when *TIP* reaches $TIP_{allowed}$.

Flowchart of Computation Procedures

The flow chart shown in Figure 8 depicts the procedure of finding the worst case TRM.

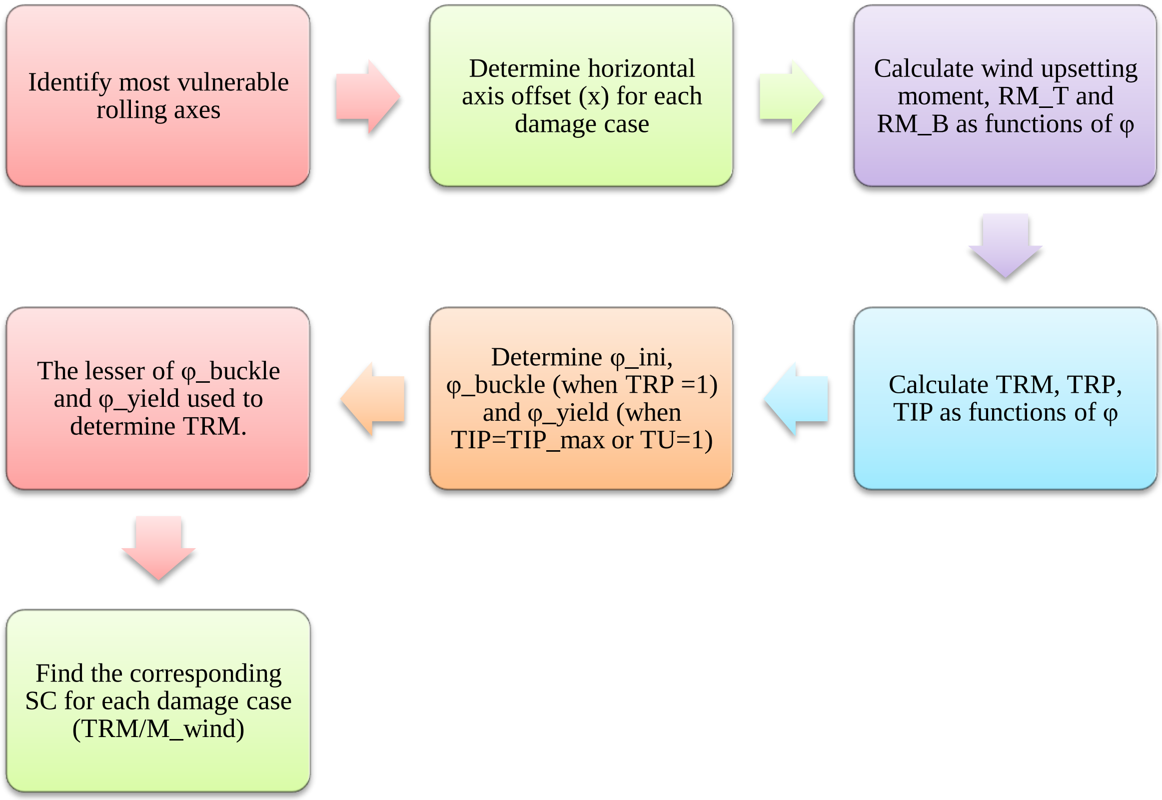


Figure 8. Flow chart

Stability of SeaStar TLP with Intact and Partially Damaged Tendon System

Now we consider the stability of the SeaStar TLP with intact or damaged tendons on a tension leg.

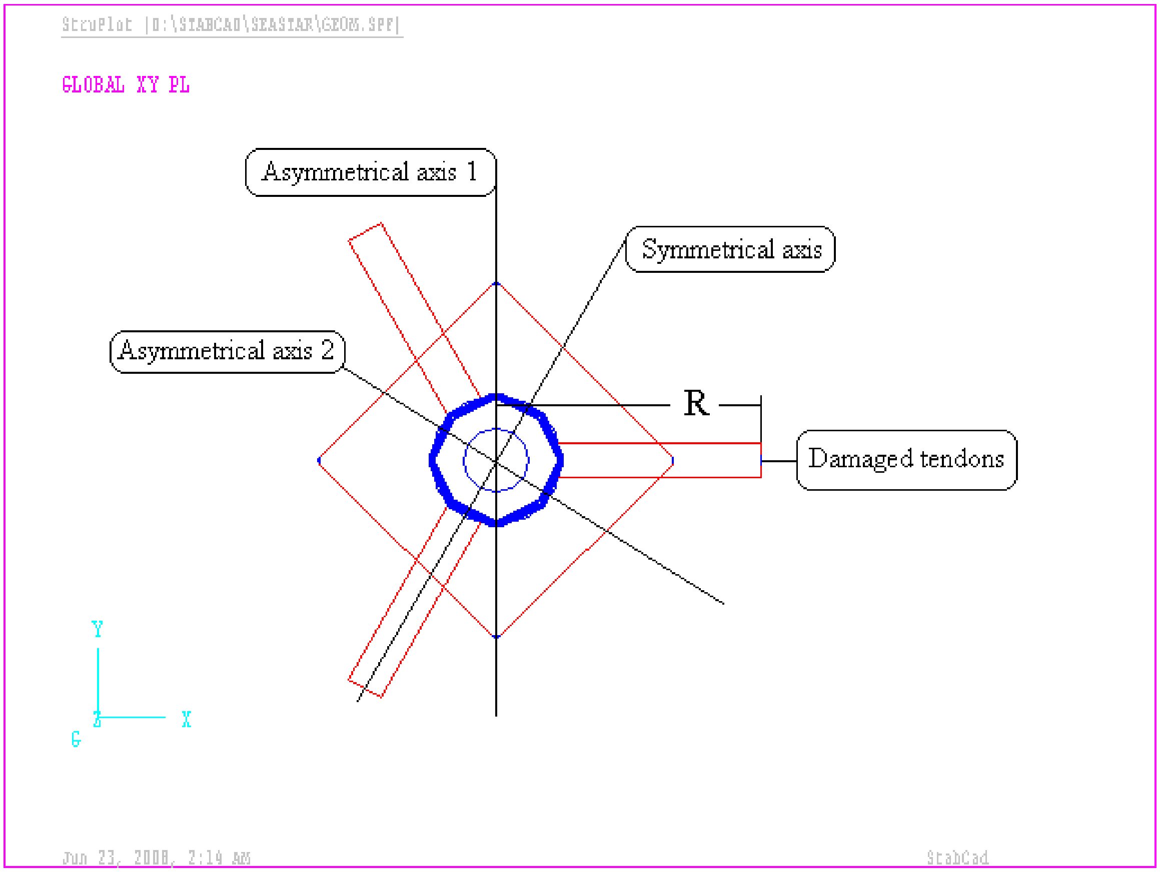


Figure 9. Rolling axis definition

Six cases are considered under this condition as shown in Figure 9, where the asymmetrical axes and the symmetrical axis are depicted. It should be noted when 1 or 2 tendons are damaged, these rolling axes will shift in parallel a certain distance, from their corresponding position when the tendon system is intact.

The six cases are defined as below:

1. Asymmetrical 1 rolling with the damaged tension leg up
2. Asymmetrical 1 rolling with the damaged tension leg down
3. Symmetrical rolling axes with the damaged tension leg up

4. Symmetrical rolling axes with the damaged tension leg down
5. Asymmetrical 2 rolling axes with the damaged tension leg up
6. Asymmetrical 2 rolling axes with the damaged tension leg down

For the case of an intact tendon system, the above six cases reduce to three. It is because, when all tendons are intact, the two asymmetrical rolling axes become identical and so are the two symmetrical rolling cases.

Righting Moment in Asymmetrical 1 Rolling

In cases where tendons on one tension leg are damaged and the hull starts to roll with respect to asymmetrical 1 axis, the related rolling axis shifts in parallel with the original asymmetrical axis at mid-hull toward the side of tension legs with intact tendons, as shown in Figure 10.

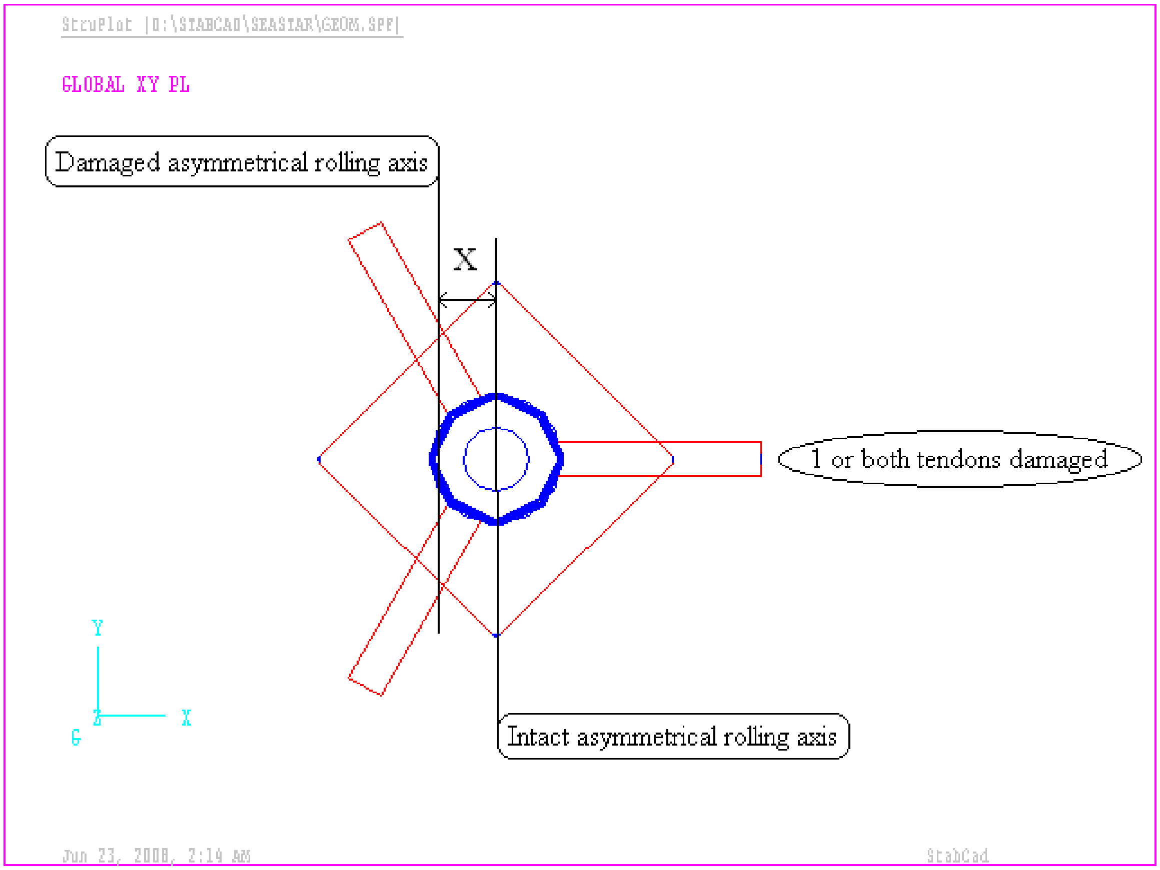


Figure 10. Shifting of asymmetrical 1 rolling axis of SeaStar TLP

To determine x, the equation is used in which the total vertical force of the remaining tendons is balanced by the difference between buoyancy and weight.

$$(2-N)(T_a+\Delta T_d)+4(T_a-\Delta T_i)=B-\Delta B-W \quad N=0,1,2 \tag{25}$$

where

$$\Delta T_d = k(R+x)\phi\,, \tag{26}$$

$$\Delta T_i = k\left(\frac{R}{2}-x\right)\phi\,. \tag{27}$$

k is the stiffness constant as defined in Equation (3). Substitute Equations (26) and (27) into Equation (25), we get

$$x = \left(\frac{N}{6-N}\right)R \quad for\ N = 0,1,2 \tag{28}$$

Tendon righting moment, RM_T, when the hull rolls to an angle ϕ can be calculated by,

$$RM_T = \begin{cases} (2-N)(T_a+\Delta T_d)(R) - 4(T_a-\Delta T_i)\left(\frac{R}{2}\right) & Damaged\ leg\ up \\ 4(T_a+\Delta T_i)\left(\frac{R}{2}\right) - (2-N)(T_a-\Delta T_d)(R) & Damaged\ leg\ down \end{cases} \tag{29}$$

$$N = 0,1,2$$

or simply

$$RM_T = [2\Delta T_i + (2-N)\Delta T_d \pm NT_a]R \quad N = 0,1,2$$

In the form of Equation (19) TRM with 1 tendon damaged can be expressed as

$$TRM_{N=1} = (2.34E10 - 9.15E08)(\phi \mp 0.8635°) \tag{30}$$

Righting Moment in Symmetrical Rolling

In cases where a tendon on one tension leg is damaged and the hull starts to roll with respect to the symmetrical axis, the related symmetrical rolling axis shifts horizontally from and in parallel with the original symmetrical rolling axis toward the tension legs with intact tendons, as shown in Figure 11.

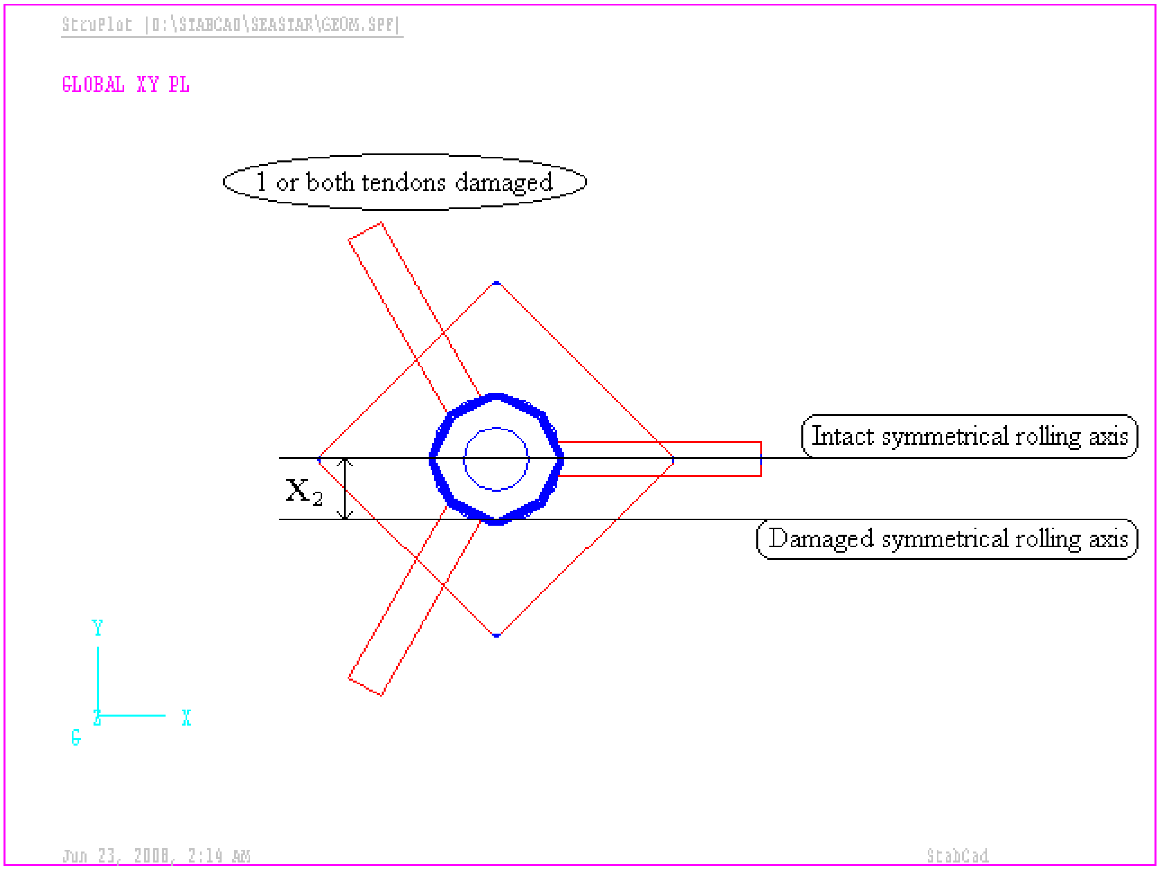


Figure 11. Shifting of symmetrical rolling axis of SeaStar TLP

We use the same method as in the asymmetrical case to find the offset, x_2

$$(2-N)(T_a+\Delta T_d)+2(T_a+\Delta T_m)+2(T_a-\Delta T_i)=B-\Delta B-W$$
$$N=0,1,2 \tag{31}$$

where

$$\Delta T_d = k\left(\frac{\sqrt{3}}{2}R+x_2\right)\phi\,, \tag{32}$$

$$\Delta T_m = kx_2\phi\,, \tag{33}$$

$$\Delta T_i = k\left(\frac{\sqrt{3}}{2}R - x_2\right)\phi\,. \tag{34}$$

Substitute Equations (32), (33) and (34) into Equation (31), we get

$$x_2 = \left(\frac{N}{6-N}\right)\frac{\sqrt{3}}{2}R \quad for\ N = 0,1,2 \tag{35}$$

The righting moment provided by tendons, RM_T, when the hull rolls at an angle ϕ can be calculated by

$$RM_T$$

$$= \begin{cases} (2-N)(T_a + \Delta T_d)\left(\frac{\sqrt{3}}{2}R\right) - 2(T_a - \Delta T_i)\left(\frac{\sqrt{3}}{2}R\right) & damaged\ leg \\ 2(T_a + \Delta T_i)\left(\frac{\sqrt{3}}{2}R\right) - (2-N)(T_a - \Delta T_d)\left(\frac{\sqrt{3}}{2}R\right) & damaged\ leg\ do \end{cases} \tag{36}$$

$$N = 0,1,2$$

or simply

$$RM_T = [2\Delta T_i + (2-N)\Delta T_d \pm NT_a]\left(\frac{\sqrt{3}}{2}R\right) \quad N = 0,1,2$$

In the form of Equation (19) TRM with 1 tendon damaged can be expressed as

$$TRM_{N=1} = (2.73E10 - 9.15E08)(\phi \mp 0.6373°) \tag{37}$$

Righting Moment in Asymmetrical 2 Rolling

In cases where tendons on one tension leg are damaged and the hull starts to roll with respect to asymmetrical 2 axis, the related rolling axis shifts in parallel with the original asymmetrical axis at mid-hull toward the side of tension legs with intact tendons, as shown in Figure 12.

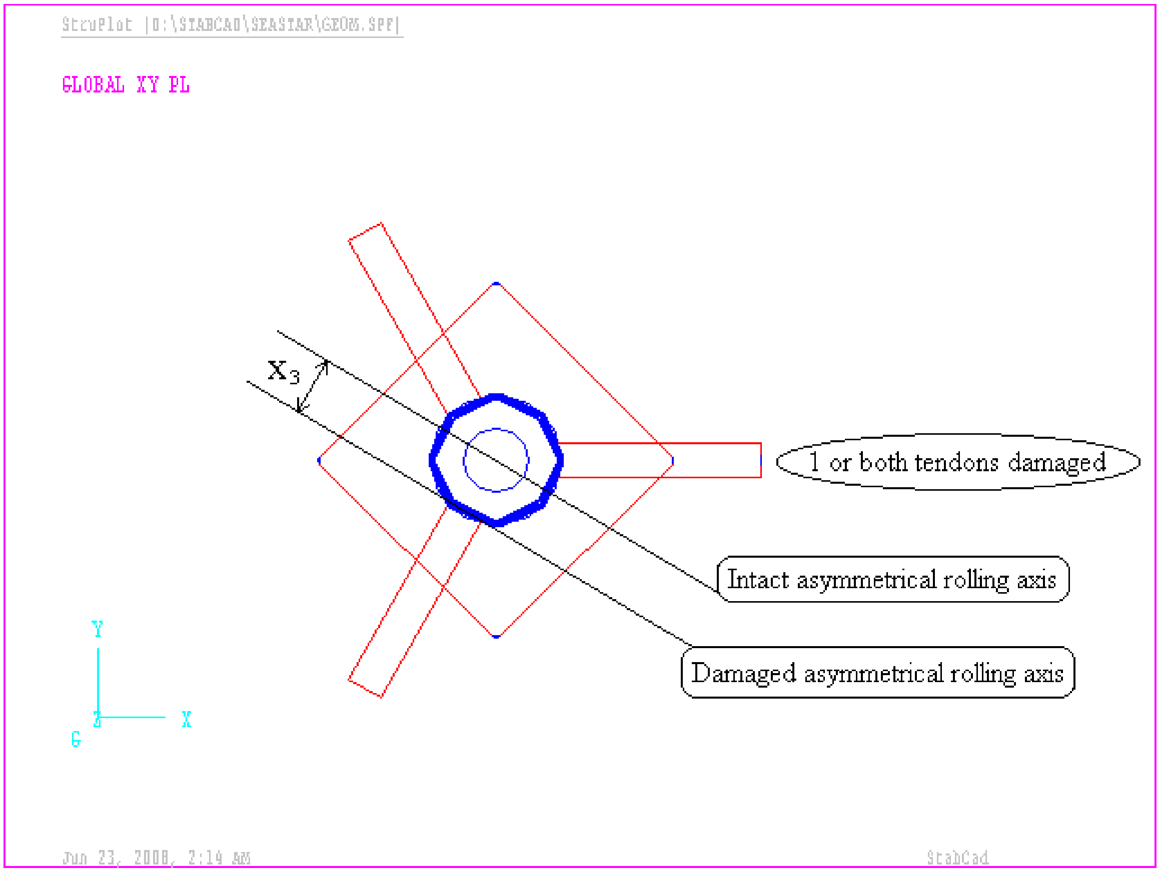


Figure 12. Shifting of asymmetrical 2 rolling axis of SeaStar TLP

Similarly, when the hull rotates about the asymmetrical 2 axis, the offset is found to be

$$x_3 = \left(\frac{N}{6-N}\right)\frac{R}{2} \quad for\ N = 0,1,2 \tag{38}$$

Tendon righting moment, RM_T, when the hull rolls to an angle ϕ can be calculated by

$$RM_T = \begin{cases} (4-N)(T_a + \Delta T_d)\left(\frac{R}{2}\right) - 4(T_a - \Delta T_i)(R) & damaged\ leg\ up \\ 4(T_a + \Delta T_i)(R) - (2-N)(T_a - \Delta T_d)\left(\frac{R}{2}\right) & damaged\ leg\ down \end{cases} \tag{39}$$

$$N = 0,1,2$$

or simply

$$RM_T = [4\Delta T_i + (4-N)\Delta T_d \pm T_a]\left(\frac{R}{2}\right) \quad N = 0{,}1{,}2$$

where

$$\Delta T_d = k\left(\frac{R}{2} + x_3\right)\phi\,, \tag{40}$$

$$\Delta T_i = k(R - x_3)\phi\,. \tag{41}$$

In the form of Equation (19) TRM with 1 tendon damaged can be expressed as

$$TRM_{N=1} = (3.50E10 - 9.15E08)(\phi \mp 0.2840°) \tag{42}$$

where $\phi_{ini} = 0.2840°$ when damaged leg up and $\phi_{ini} = -0.2840°$ when damaged leg down.

For intact condition rolling about any axis orientation across the mid hull,

$$TRM_{N=0} = (3R^2k + \overline{BM}(B - \Delta B) - \overline{BG}W)\phi \tag{43}$$

or

$$TRM_{N=0} = (3.89E10 - 9.15E08)\phi$$

Stability of E-TLP and Moses TLP with Intact and Partially Damaged Tendon System

Equations of TRM and TRP calculations for the E-TLP and Moses TLP are similar to those of the C-TLP, because of their similarities in hull shape, thus the derivations will not be repeated.

CHAPTER IV

WIND PROFILE

API Wind Profile

It is assumed that the wind speed is horizontally uniform but varies with the height above the sea surface according to a power law profile (API, 2005),

$$\overline{U}(z) = \overline{U}_{ref} \left(\frac{z}{z_{ref}}\right)^{0.125} \tag{44}$$

where z is the elevation above mean sea level, the reference elevation is 10 m and the 1-hour mean speed at that reference elevation is denoted as $\overline{U}_{ref}$.

The turbulence intensity (API, 2005) is given as

$$I(z) = \frac{\sigma_u(z)}{\overline{U}(z)} = \begin{cases} 0.15\left(\frac{z}{z_s}\right)^{-0.125} & for\ \frac{z}{z_s} \leq 1 \\ 0.15\left(\frac{z}{z_s}\right)^{-0.275} & for\ \frac{z}{z_s} > 1 \end{cases} \tag{45}$$

where $z_s = 20\ m$, indicating the thickness of the air "surface layer".

The relation for gust factor (API, 2005) is given as

$$g(T) = 3.0 + ln\left[\left(\frac{3}{T}\right)^{0.6}\right]\ \ for\ T \leq 60\ seconds \tag{46}$$

The average wind velocity over periods much shorter than one hour, such as the average 1-minute wind speed or the average 3-second gust speed is of our interest. The information can be used in quasi-static design analysis of individual elements of the platform superstructure.

The formula for the gust wind speed at any height above MSL is expressed as

$$\overline{U}(z,t) = \overline{U}(z)[1 + g(T)I(z)] \tag{47}$$

Wind Speed Selected for Computing Upsetting Moment

100-year hurricane has been widely used as an important design criterion of offshore floating structures. Sections in API RP 2T that reference "extreme" conditions should generally be taken as 100-year return period conditions based on API Bulletin 2INT-MET values. Reduced extreme conditions (e.g. damaged ballast conditions) should not be less than equivalent 10-year return period conditions (API, Interim Guidance for Design of Offshore Structures for Hurricane Conditions, 2007).

The Pre-Katrina GOM 100-year wind speed of 41 m/s (API, Interim Guidance on Hurricane Conditions in the Gulf of Mexico, 2007), the 1-hour averaged wind speed at 10 meters above Mean Sea Level (MSL), is used. The 60-second average gust wind speed at 10 meters above MSL was used as our input wind speed for StabCAD. According to the input information of the hull and the topside superstructures, StabCAD will compute the center pressure based on the input wind speed, which will lead to the wind upsetting moment applied on the TLP. Based on the API wind model, the 1-hour average wind speed of 41 m/s leads to 60-second gust wind speed of 50.1 m/s, at 10 m above MSL. It should be noted that this number agrees well with the required 100-knot (51.4 m/s) 1-hour wind speed specified in the ABS MODU Rules (ABS, 2001).

CHAPTER V

RESULTS AND DISCUSSION

Stability of C-TLP with Intact and Partially Damaged Tendon System

As mentioned in Chapter III, the two major rolling cases considered for analyzing the stability of the C-TLP are strict tilt and diagonal tilt.

Figure 13 shows a comparison between these two cases of C-TLP with an intact tendon system regarding the TRM and the TRP/TIP of the tendons due to inclination. When TRP reaches 100% or TIP reaches its allowed percentage, whichever comes first, it is considered failure for those tendons.

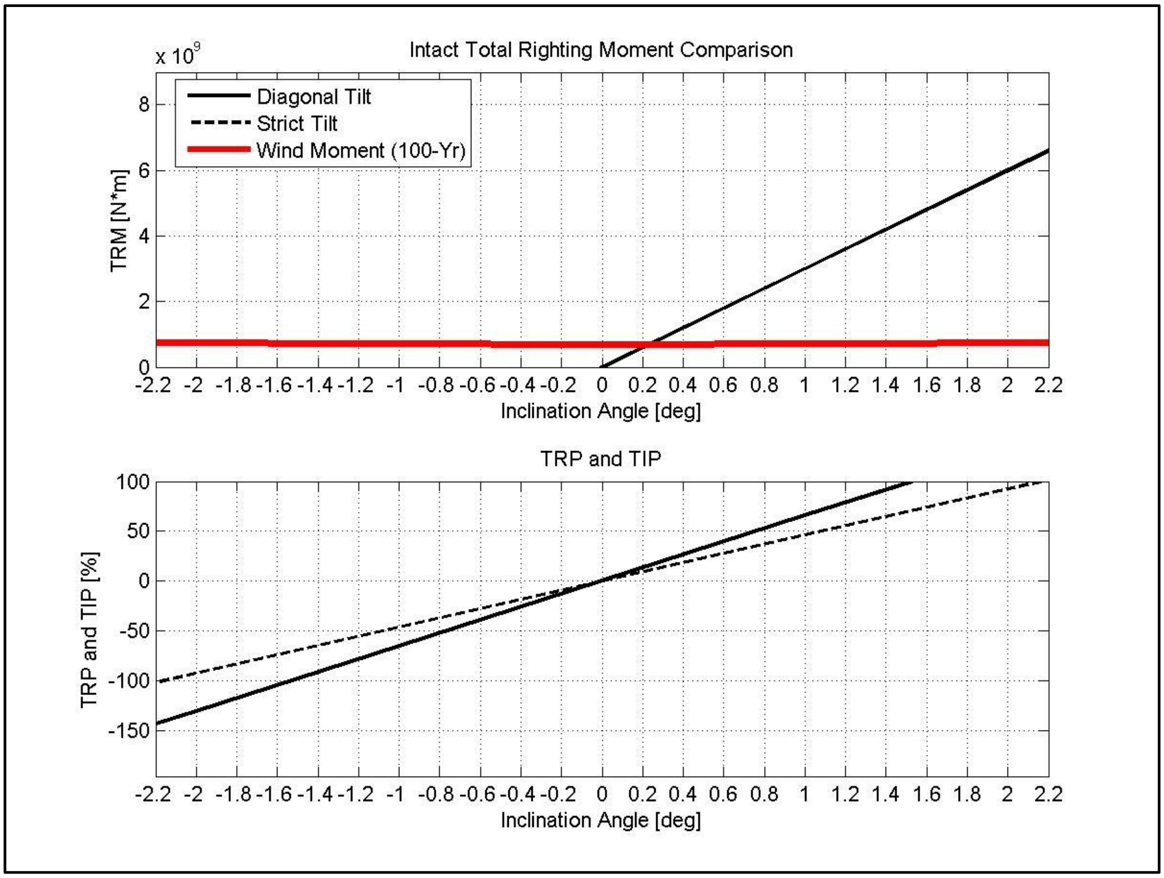


Figure 13. TRM of C-TLP (intact)

As one can tell from Figure 13, both cases provide the same exact TRM at any given inclination angle, as expected.

Despite having the same TRM, the rate of TRP/TIP in the two cases varies due to the difference in axis orientation. TRP reaches 100% when the hull is inclined to 1.5 degrees in the diagonal tilt case, which is significantly less than the 2.1 degrees in the strict tilt case. This is due to the larger distance from the tendons to the center of the hull, by a factor of $\sqrt{2}$. We can now conclude that the worst scenario is the diagonal tilt case, as its lower end tendons lose their tension or up leg tendons reaches their yield tension at a faster rate under the same magnitude of upsetting moment, thus offering less range of stability. Therefore, in the rest of this chapter, we only present the results related to the rolling stability in the diagonal tilt case, which is the most vulnerable case. In the case of C-TLP with intact tendons, TRM is 6.75 times the upsetting moment when TRP reaches 100% at 1.5 degrees. We name this ratio the Spare Capacity (SC) for the purpose of description. It should be noted that this number should not be confused with Safety Factor (SF) because wave and current induced upsetting moments are not considered here. SC only indicates how statically stable a TLP is against an extreme (1-minute) wind gust during a 100-year hurricane.

We now consider the rolling stability of the C-TLP with 1, 2 and 3 tendons damaged when on one of its tension leg. Two sub-cases are considered for each of the main cases: damaged tension leg up (leg with damaged tendons tilting upward) and damaged tension leg down (leg with damaged tendons tilting downward).

Figures 14, 15 and 16 show the TRM plots for 1 tendon damaged case, 2 tendons damaged case and 3 tendons damaged case, respectively.

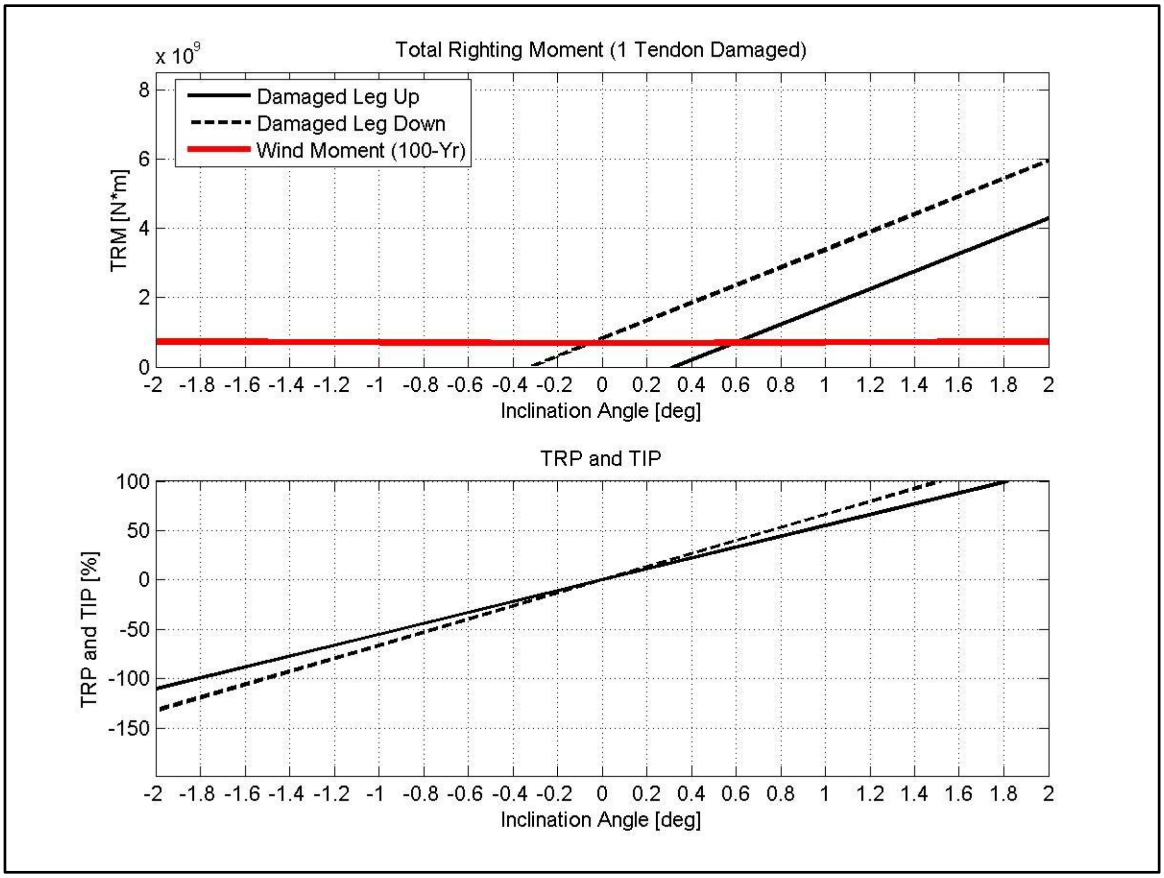


Figure 14. TRM of C-TLP (1 tendon damaged)

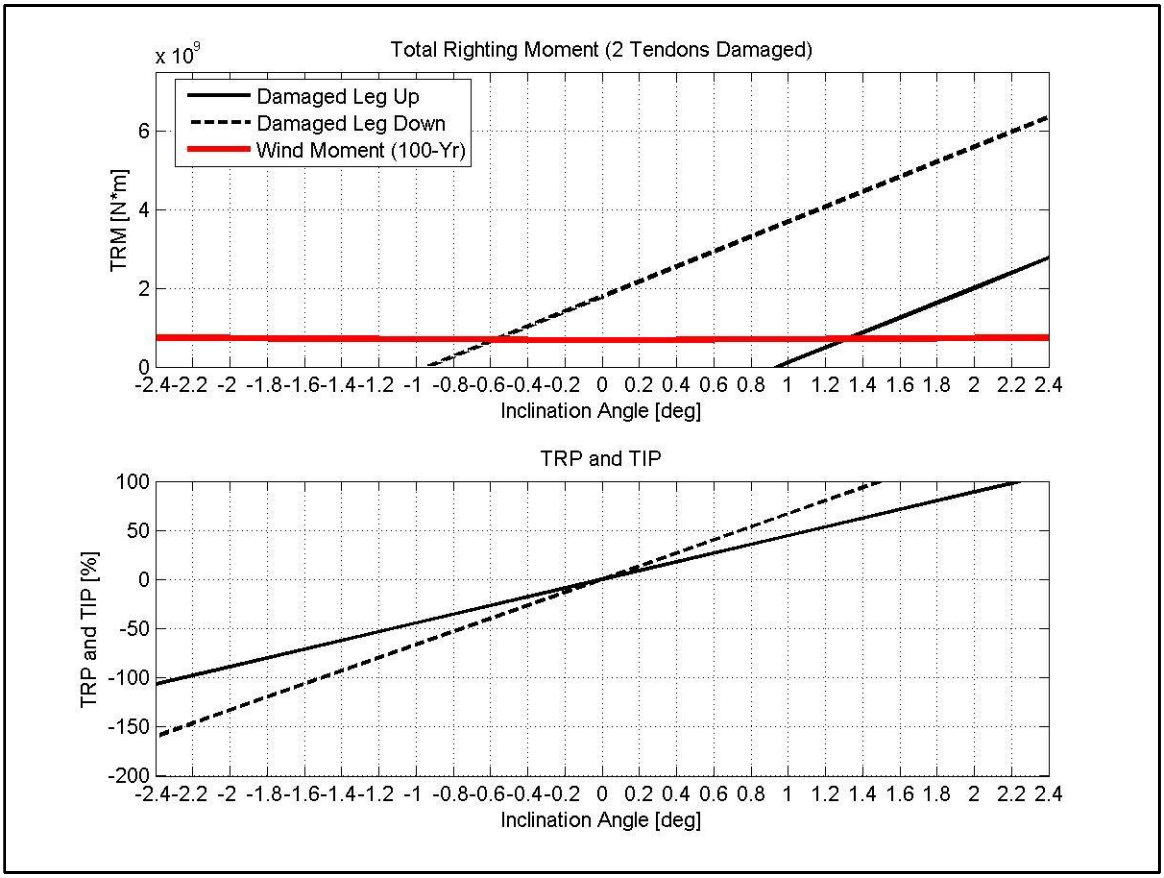


Figure 15. TRM of C-TLP (2 tendon damaged)

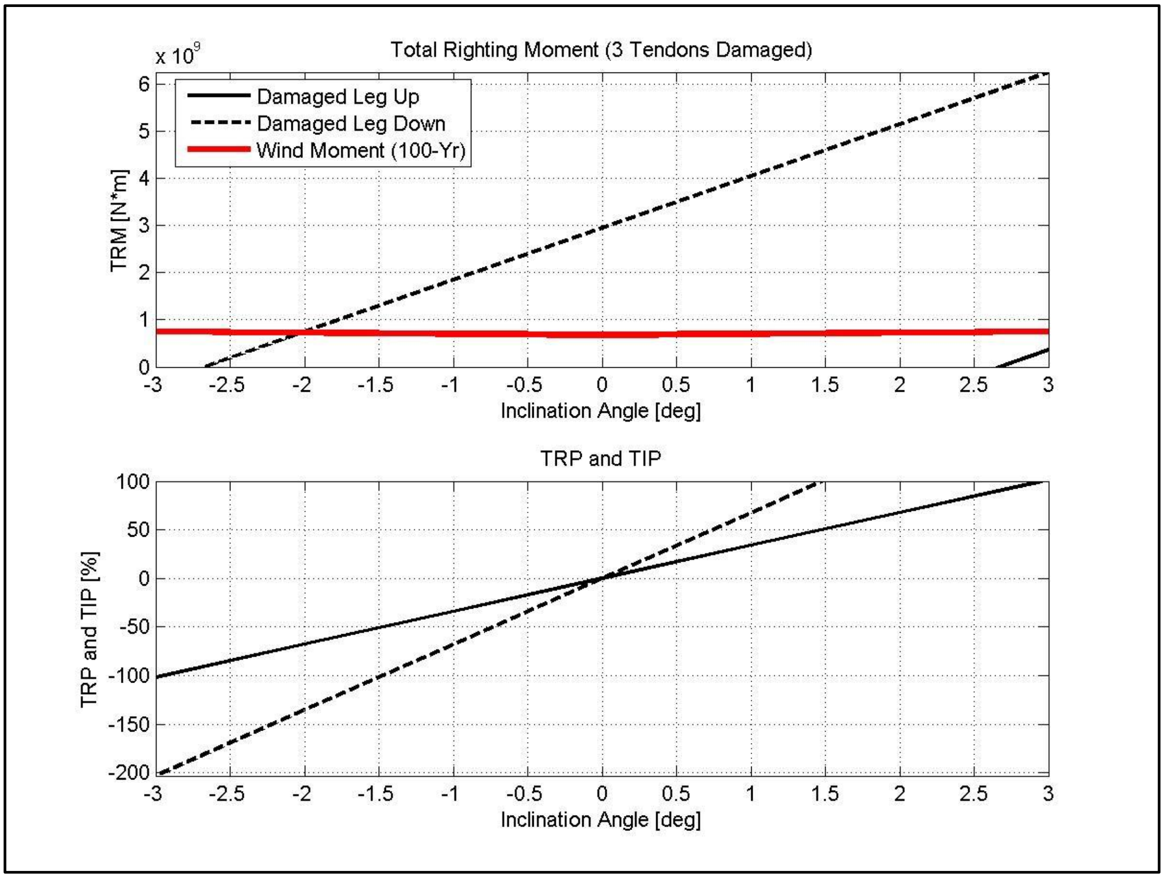


Figure 16. TRM of C-TLP (3 tendon damaged)

In the case when 1 tendon is damaged, in the absence of any upsetting moment from the environment, the hull has a 0.3223 degree of initial inclination at its equilibrium position. That is, the hull inclination leads to a smaller tension in tendons located at the corner opposite to the corner having damaged tendons. In the damaged tension leg down case, the remaining tendons on the damaged tension leg start to buckle at 1.5 degrees while the system provides 4.6×10^9 N*m of TRM. In the damaged tension leg up case, the lower leg tendons starts to buckle and the up leg tendons start to yield at 1.8 degrees of inclination, a seemingly larger range of stability, but the system provides only 3.8×10^9 N*m of TRM, resulting in a SC of 5.58. Therefore we can predict that the damaged tension leg up case is the more vulnerable of the two in cases with 2 or 3 damaged tendons as well. SC for 1 tendon damaged and 2 tendon damaged cases are found to be 5.58 (due to buckling and yielding) and 1.76 (due to yielding), respectively. When 3 tendons are damaged, SC becomes negative. In this case, the tendons on the tension leg opposite to the damaged tension leg will buckle and eventually lose their function. After these three tendons lose their function, the remaining tendons will lose their function, and the righting moment to prevent rolling with respect to the diagonal of the hull will be provided only by buoyancy and weight.

Table 2 summarizes the results for the C-TLP for all intact and damage cases. The critical angles in bold are the smaller angles which we used to determine TRM and SC. Wind upsetting moments, averaged tensions and initial angles for each case are included in the table. We use the relative angle $\phi_{rel} = \phi - \phi_{ini}$ for buckling and yielding angles. By doing so, we are able to gain a clearer view when identifying the most vulnerable cases. In the N tendon(s) damaged case, we are able to select the lowest of four critical angles (2 for damaged leg up, 2 for damaged leg down) and assign the corresponding case as the most vulnerable case to find the lowest TRM and SC. The constants C_1, C_{2t} and C_{2b} are included for checking purposes. Buoyancy contribution is defined as $\frac{C_{2b}}{C_{2t}+|C_{2b}|} \times 100\%$ and buoyancy adjustment percentage is defined as $\frac{\Delta B}{B} \times 100\%$. These two terms were introduced to show the importance of buoyancy righting moment and the change in buoyancy due to tendon damage.

Table 2. Summary of C-TLP's intact and partially damaged stabilities

Cases (Diagonal)		M_wind (N*m)	Ta (N)	TTP_allowed (%)	φ_ini (deg)	(φ-φ_ini)_buckle (deg)	(φ-φ_ini)_yield (deg)	TRM (N*m)	SC	C1 (N*m)	C2_t (N*m/radian)	C2_b (N*m/radian)	Buoyancy contrib (%)	Buoyancy adj perc (%)
Intact		6.82E+08	1.35E+07	135	0	**1.5**	2.0	4.6E+09	**6.75**	0	1.72E+11	6.19E+09	3.5	0.00
1 damaged	Dmg leg up		1.46E+07	117	0.32	**1.5**	**1.5**	3.8E+09	**5.58**	-8.25E+08	1.41E+11	6.15E+09	4.2	0.32
	Dmg leg down				-0.32	1.8	2.5	4.6E+09	6.75	8.25E+08				
2 damaged	Dmg leg up		1.59E+07	100	0.94	1.3	**0.6**	1.2E+09	**1.76**	-1.79E+09	1.03E+11	6.10E+09	5.6	0.69
	Dmg leg down				-0.94	2.4	3.2	4.7E+09	6.90	1.79E+09				
3 damaged	Dmg leg up		1.74E+07	82	2.67	0.2	**-1.5**	Negative	**Negative**	-2.95E+09	5.73E+10	6.05E+09	9.6	1.03
	Dmg leg down				-2.67	4.2	5.1	N/A		2.95E+09				

Stability of C-TLP with a Completely Damaged Tendon System

When considering the static stability of the C-TLP losing all its tendons, we obtain the stability curves using StabCAD. The capability of StabCAD was briefly mentioned in the introduction. Established stability standards for all types of vessels, including semi-submersibles and TLPs, are quasi-static in character. It has nonetheless been recognized that the actual performance of a MODU in severe conditions depends to a large extant on its dynamic behavior. Conventional standards take no explicit account of wave and current conditions. They compare the steady wind heeling moment curve with the hydrostatic righting moment curve, both curves being plotted as functions of the hull's inclination angle about its 'most critical axis' (e.g. longitudinal axis for conventional ship, diagonal axis for 4-column TLPs, etc.), as shown in Figure 17.

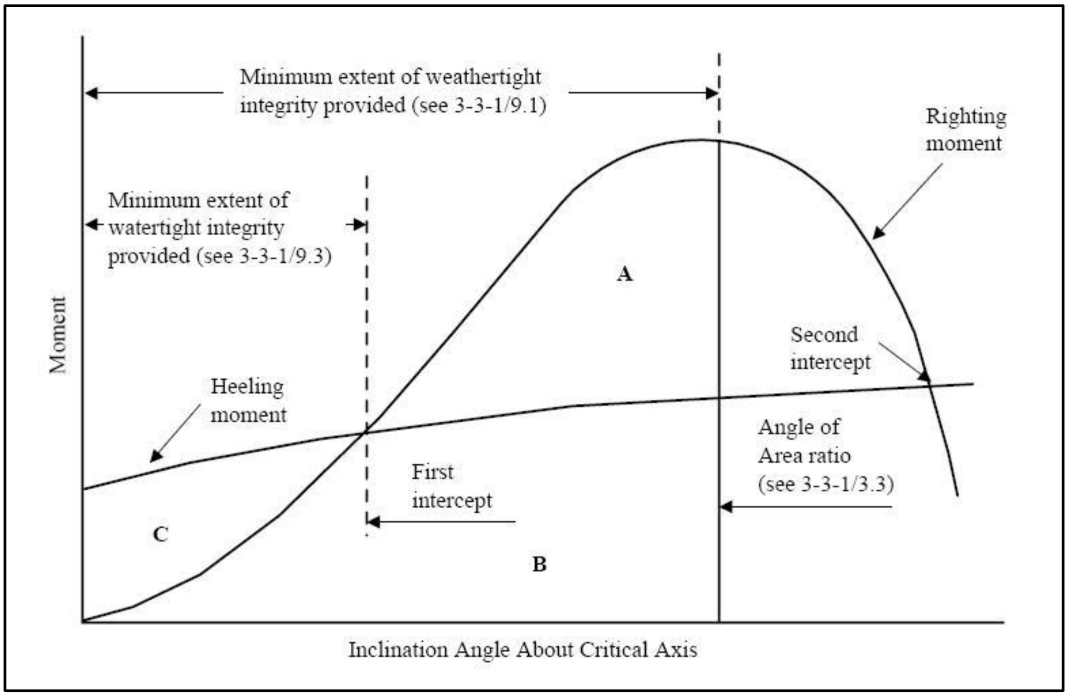


Figure 17. Stability curves for large heeling angle

In this study we use the intact stability criteria stated in ABS MODU rules (See Part III, Chapter 3): All units are to have positive metacentric height in calm water equilibrium position, for all afloat conditions, including temporary positions when raising or lowering. For column-stabilized units, the area under the righting moment curve at or before the second intercept angle or the downflooding angle, whichever is less, is to reach a value of not less than 30% in excess of the area under the wind heeling moment curve to the same limiting angle. In all cases, the righting moment curve is to be positive over the entire range of angles from upright to the second intercept angle (ABS, 2001). Thus, the area ratio under the heeling and righting moment curves has to satisfy the criterion $A + B > 1.3(B + C)$ when areas A, B and C are integrated up to the second intercept in our case.

The area ratio criterion essentially compares the potential energy gained by the hull through its righting moment with the work done by the wind heeling moment during a steady wind gust which inclines the hull from its upright position to the capsizing angle. The area A+B represents the work done by the righting moment of the hull, and the area B+C represents the work done by the wind heeling moment. The safety factor 1.3 is common to the rules of most regulatory bodies, and is intended to make allowance for uncertainties and dynamic effects which are not taken into account in the analysis.

As shown in Figure 18, buoyancy alone offers the C-TLP satisfactory stability according to ABS standards for column stabilized units. The stability curve has an area ratio of 1.66. The static heel angle (first intercept) and the capsizing heel (second intercept) angle are 13 degrees and 58 degrees, respectively. The hull has a metacentric height, GM, of 7.1 m at its freely floating draft of 14.7 m. The allowable KG is 30.81 m under the 1.3 area ratio requirement.

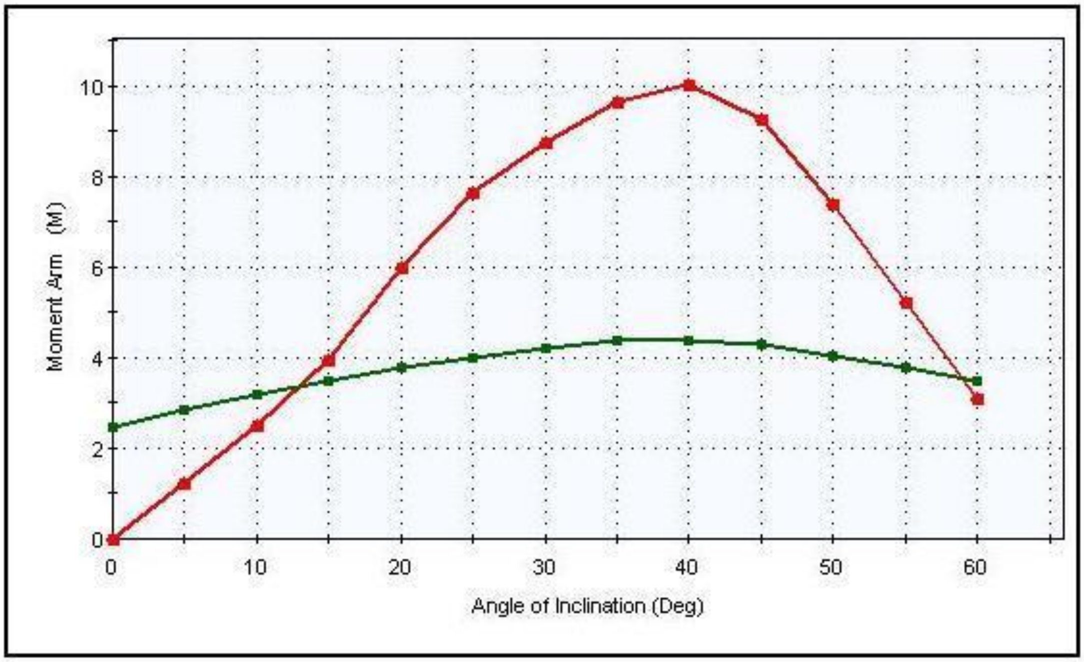


Figure 18. Floating stability curves of C-TLP

Stability of SeaStar TLP with Intact and Partially Damaged Tendon System

Three cases were considered for analyzing the static stability of the SeaStar TLP with an intact tendon system: two for the asymmetrical case (single leg up and single leg down) and one for the symmetrical case (identical between clockwise and anticlockwise inclinations).

Figure 19 shows a comparison of these three cases on the intact TRM and TRP of the lower end tendons due to inclination. Once again, all three cases result in exactly the same TRM at any given inclination angle. It is the rate of TRP that varies with rolling axis orientations, as in the case of the C-TLP. The difference factor between the best and worst cases is 2.

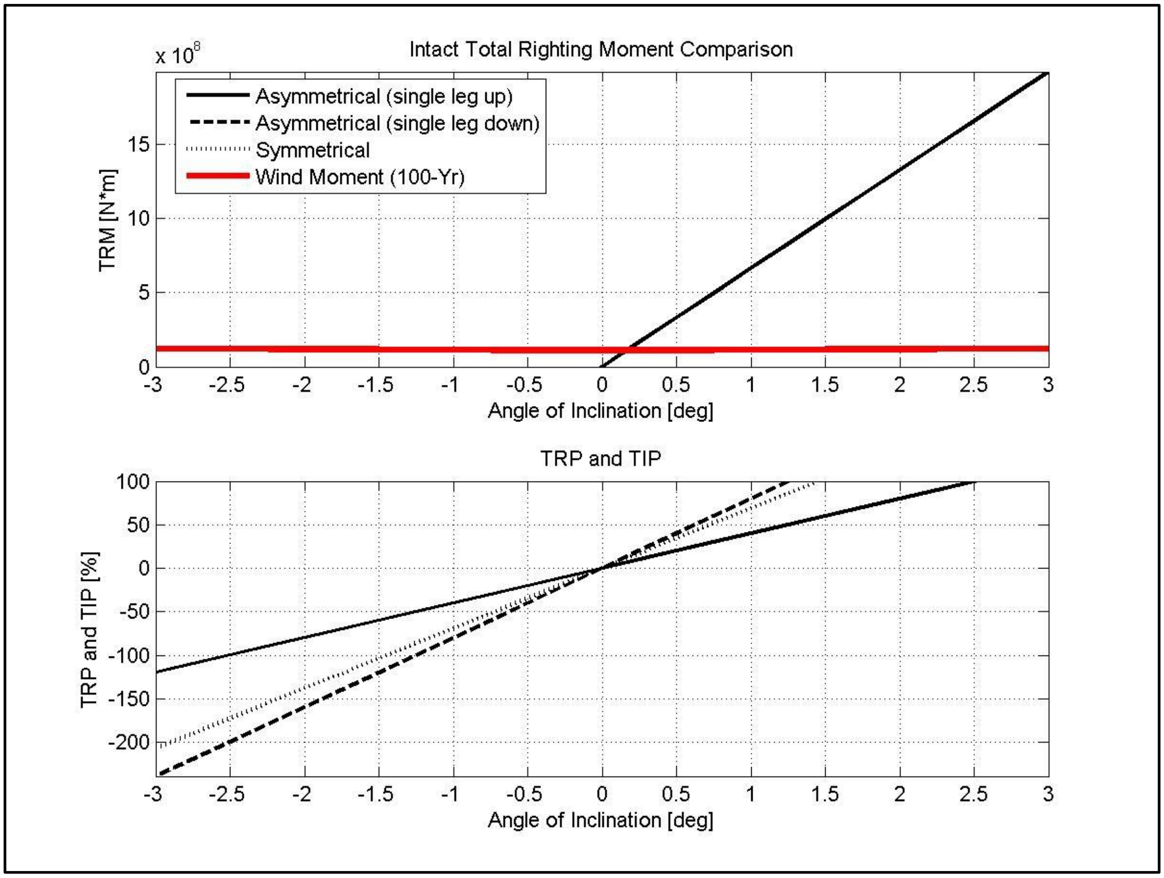


Figure 19. TRM of SeaStar TLP (intact)

As shown in Figure 19, Asymmetrical (single leg down) is the most vulnerable with a SC of 7.42 (due to buckling). However, due to the geometric complexity of the SeaStar hull, we still need to determine the most vulnerable rolling axis orientation with damaged tendons. Therefore, six cases were considered when it comes to partially damaged stability.

We now consider the rolling stability of the SeaStar TLP with 1 tendon damaged on one tension leg. Asymmetrical 1 (damaged tension leg up) is found to be the most vulnerable cases with a SC of 1.81 (due to yielding). Figures 20 shows the TRM plots for the 1 tendon damaged case.

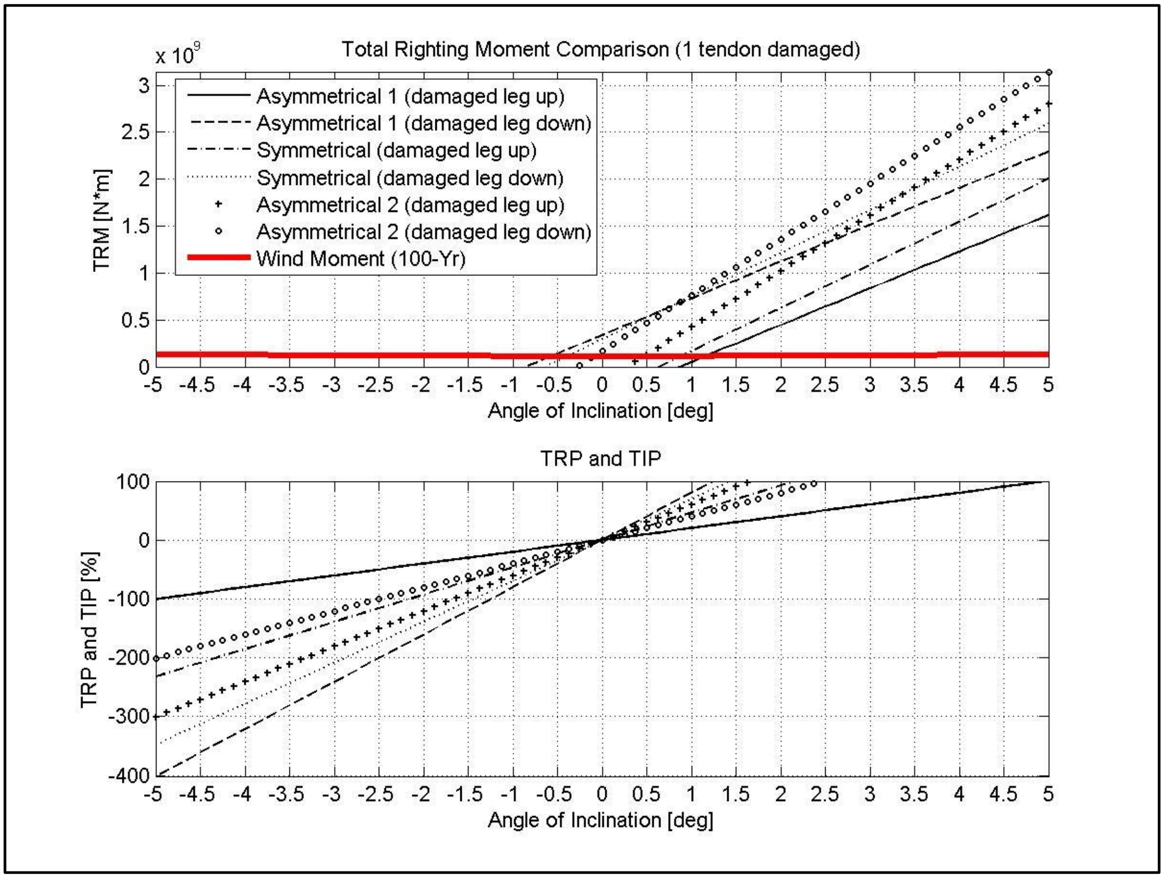


Figure 20. TRM of SeaStar TLP (1 tendon damaged)

Table 3 summarizes the results for the SeaStar TLP for all intact and damage cases. The critical angles in bold are the lower angles which we used to find TRM and SC.

Table 3. Summary of SeaStar TLP's intact and partially damaged stabilities

Cases			M_wind (N*m)	Ta (N)	TTP_allowed (%)	φ_ini (deg)	(φ+φ_ini)_buckle (deg)	(φ+φ_ini)_yield (deg)	TRM (N*m)	SC	C1 (N*m)	C2_t (N*m/radian)	C2_b (N*m/radian)	Buoyancy contrib (%)	Buoyancy adj perc (%)
Intact	Sym		1.10E+08	8.09E+06	156	0	1.4	2.2	9.50E+08	8.60	0	3.89E+10	-9.15E+08	-2.3	0.00
	Asym	Single leg up					2.5	1.9	1.30E+09	11.77					
		Single leg down					**1.3**	3.8	8.2E+08	**7.42**					
1 damaged	Asym 1	Dmg leg up		9.64E+06	114	0.86	4.0	**0.4**	2.0E+08	**1.81**	-3.38E+08	2.34E+10	-9.15E+08	-3.8	0.35
		Dmg leg down				-0.86	2.1	6.0	8.0E+08	7.24	3.38E+08				
	Sym	Dmg leg up				0.64	1.5	1.0	4.5E+08	4.07	-2.93E+08	2.73E+10		-3.2	
		Dmg leg down				-0.64	2.0	2.9	9.0E+08	8.15	2.93E+08				
	Asym 2	Dmg leg up				0.28	1.4	2.4	8.5E+08	7.69	-1.69E+08	3.50E+10		-2.5	
		Dmg leg down				-0.28	2.7	2.0	1.3E+09	11.32	1.69E+08				
2 tendons damaged	Capsize will occur when both tendons on the same leg are damaged (TRM << 0)														

When both tendons are damaged on one tension leg in the asymmetrical (damaged tension leg up) case, the remaining tendons on the two legs on the opposite side will buckle immediately. Capsize will occur in this extreme case because RM_B is negative for SeaStar TLP, and the hull is not able to provide any freely floating stability with all tendons damaged, as will be discussed in the next section.

Stability of SeaStar TLP with a Completely Damaged Tendon System

As shown in Figure 21, the righting arm becomes negative (i.e. center of gravity above metacenter) when the platform is inclined at a very small angle, the righting moment provided by the buoyancy and weight is negative. It is mainly due to its limited water-plane area from the single piercing column design. Therefore, at its freely floating draft of 8.1 m, the SeaStar TLP is not able to float upright on its own due to a -23.0 m metacentric height, hence can be classified as unstable.

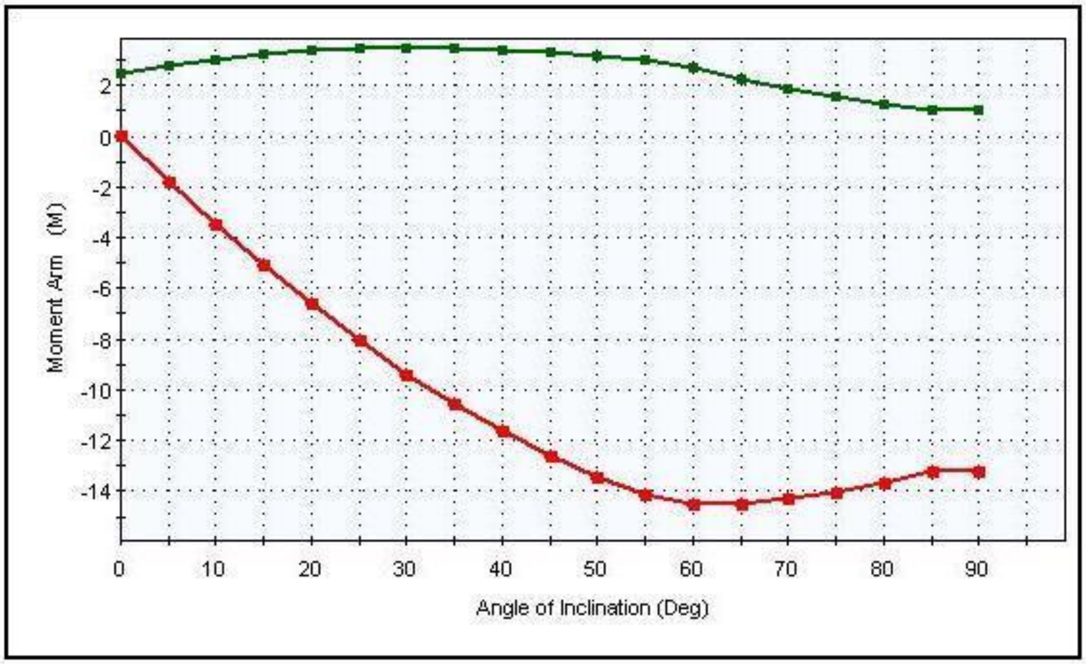


Figure 21. Floating stability curves of SeaStar TLP

Stability of E-TLP with Intact and Partially Damaged Tendon System

Similar to C-TLP, E-TLP has four columns. However, major differences exist between these two TLPs: The E-TLP has 2 tendons on each tension leg as oppose to 3 in the case of C-TLP; The E-TLP we selected has a much smaller topside windage area compared to that of the C-TLP (i.e. creating significantly less upsetting moment from wind); The E-TLP is much shorter in length between two neighboring columns and thus provide less TRM from both buoyancy and tendons when inclined.

Figures 22, 23 and 24 show the TRM plots of the E-TLP for intact case, 1 tendon damaged case and 2 tendons damaged case, respectively.

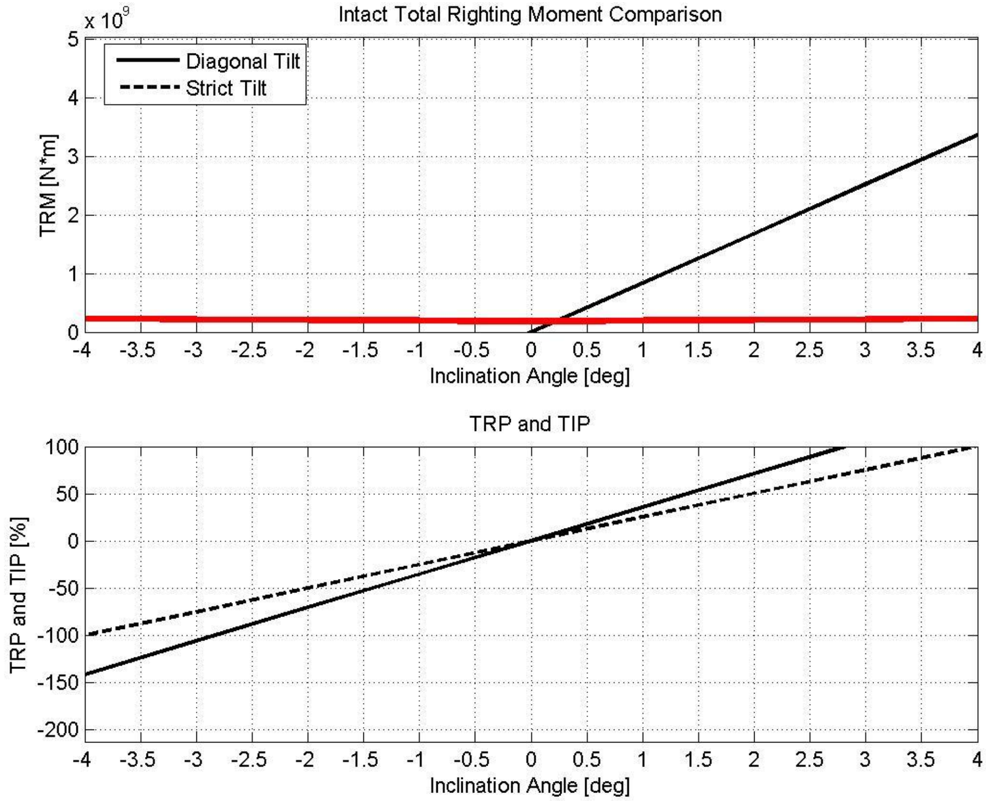


Figure 22. TRM of E-TLP (intact)

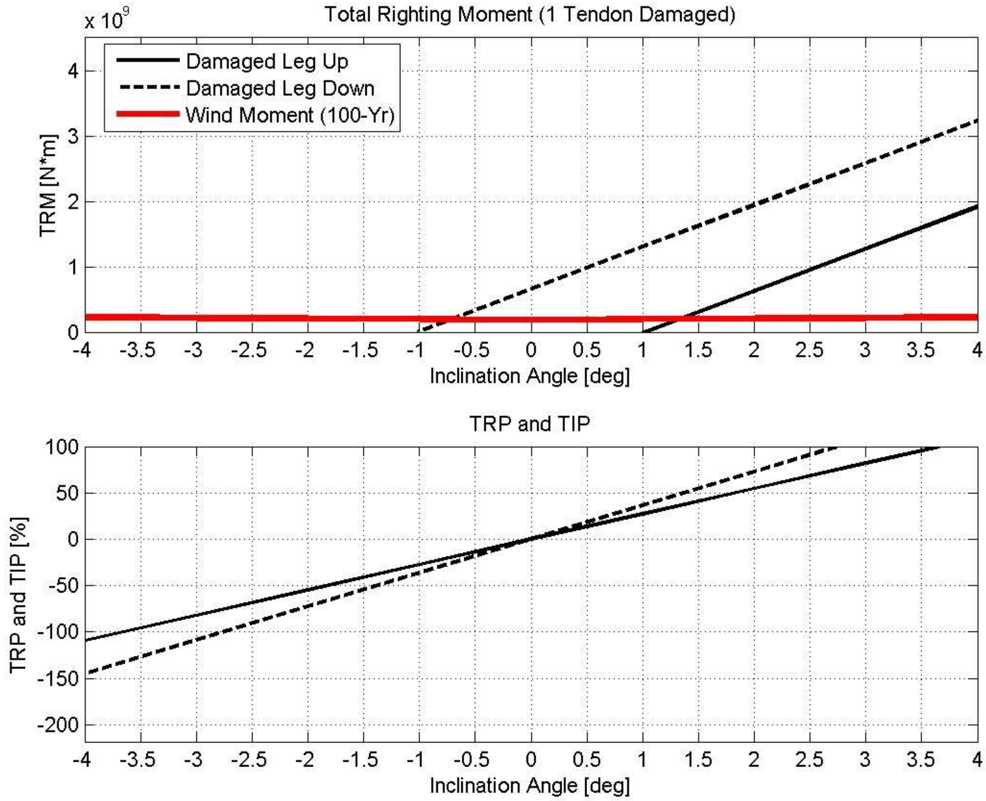


Figure 23. TRM of E-TLP (1 tendon damaged)

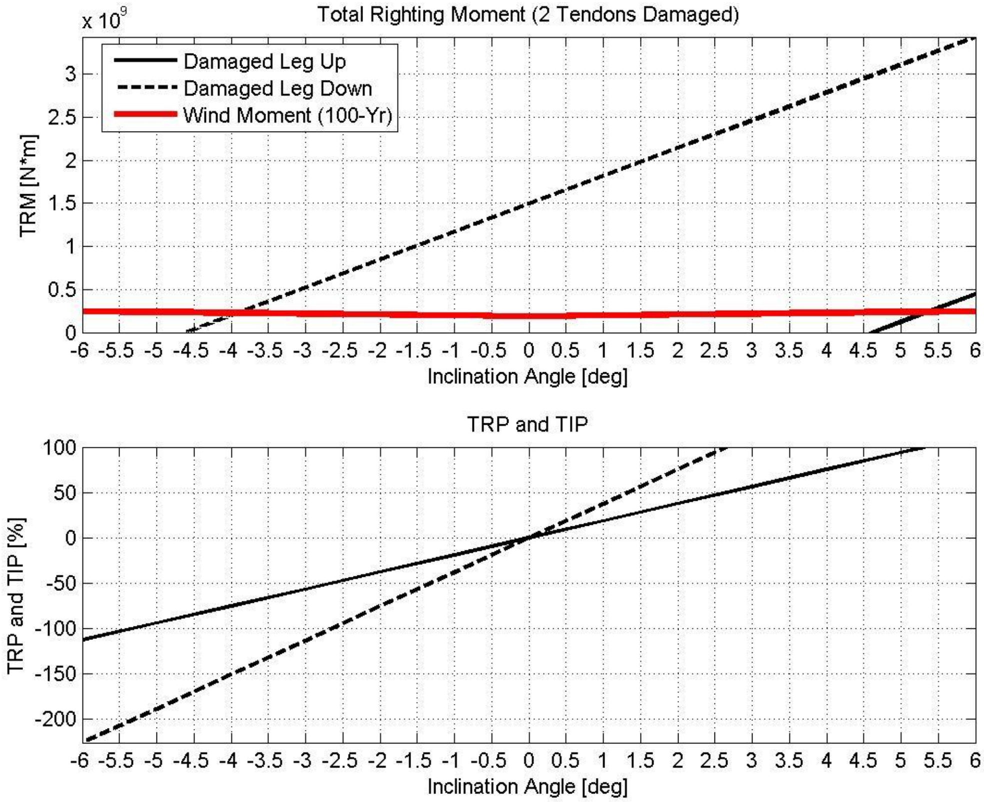


Figure 24. TRM of E-TLP (2 tendon damaged)

Using the same method as for the C-TLP, we found SC of the E-TLP to be 12.21 (due to buckling), 7.96 (due to yielding) and Negative (due to yielding) for intact case, 1 tendon damaged case and 2 tendons damaged case, respectively. The relatively small deck area helped reduce wind load, resulting in an increased SC compared to those of the C-TLP. Table 4 summarizes the results for the E-TLP for all intact and damage cases. The critical angles in bold are the lower angles which we used to find TRM and SC.

Table 4. Summary of E-TLP's intact and partially damaged stabilities

Cases (Diagonal)		M_wind (N*m)	Ta (N)	TTP_allowed (%)	φ_ini (deg)	(φ-φ_ini)_buckle (deg)	(φ-φ_ini)_yield (deg)	TRM (N*m)	SC	C1 (N*m)	C2_t (N*m/radian)	C2_b (N*m/radian)	Buoyancy contrib (%)	Buoyancy adj perc (%)
Intact		1.88E+08	1.28E+07	148	0	**2.8**	4.0	2.3E+09	**12.21**	0	4.83E+10	2.56E+09	5.0	0.00
1 damaged	Dmg leg up		1.43E+07	122	1.02	2.6	**2.4**	1.5E+09	**7.96**	-6.60E+08	3.45E+10	2.52E+09	6.8	0.75
	Dmg leg down				-1.02	3.7	5.2	2.4E+09	12.74	6.60E+08				
2 damaged	Dmg leg up		1.62E+07	96	4.61	0.7	**-2.1**	Negative	**Negative**	-1.49E+09	1.61E+10	2.46E+09	13.3	1.69
	Dmg leg down				-4.61	7.3	9.6	N/A		1.49E+09				

Stability of E-TLP with a Completely Damaged Tendon System

Analysis of completely damaged stability of the E-TLP yields comparable results with those of the C-TLP. As shown in Figure 25, buoyancy alone offers the hull very good stability. The stability curve has an area ratio of 1.90. The static heel angle and the capsizing angle are 11 degrees and 48 degrees, respectively. The E-TLP hull has a metacentric height, GM, of 6.6 m at its freely floating draft of 14.6 m. The allowable KG is 28.43 m under the 1.3 area ratio requirement.

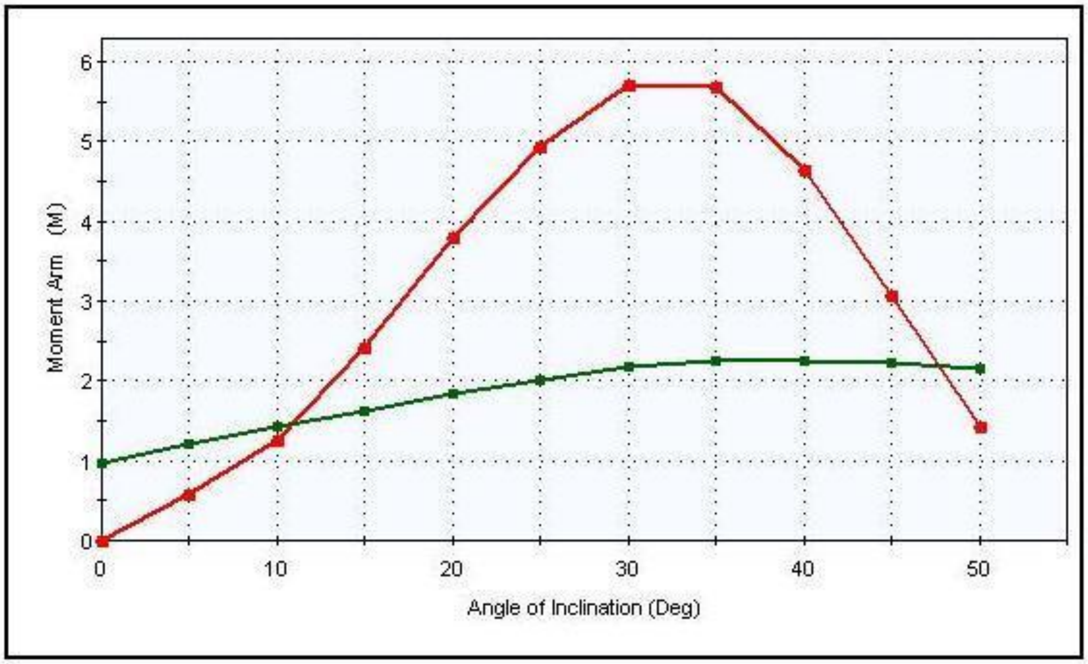


Figure 25. Floating stability curves of E-TLP

Stability of Moses TLP with Intact and Partially Damaged Tendon System

There are a few major architectural differences between the Moses TLP and the C-TLP: The Moses TLP has 2 tendons on each tension leg as oppose to 3 on the C-TLP; The Moses TLP columns are very slim and closer to the center, thus providing less righting moment from buoyancy and weight when inclined; The distance between two neighboring tension legs is extended thus provides larger TRM than that of other hull types when inclined at the same angle.

Figures 26, 27 and 28 show the TRM plots of the Moses TLP for intact case, 1 tendon damaged case and 2 tendon damaged case, respectively.

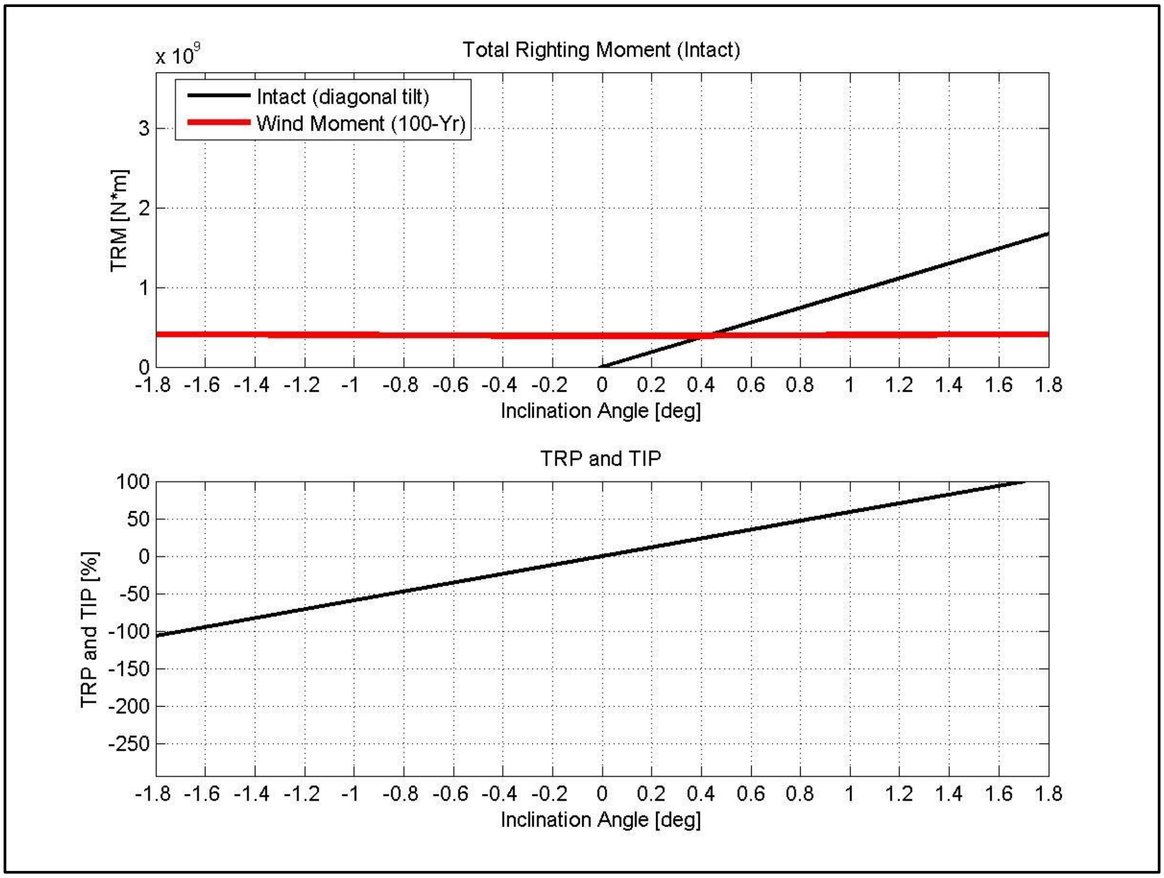


Figure 26. TRM of Moses TLP (intact)

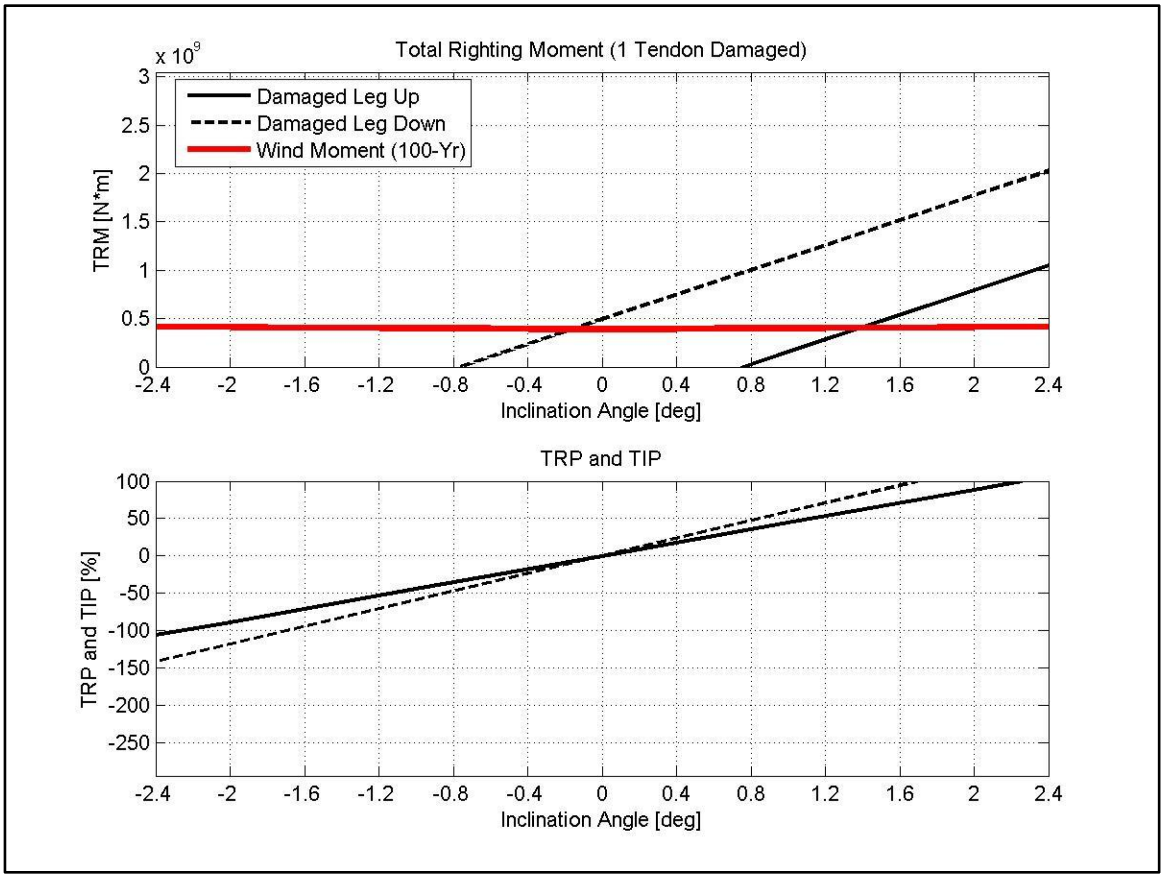


Figure 27. TRM of Moses TLP (1 tendon damaged)

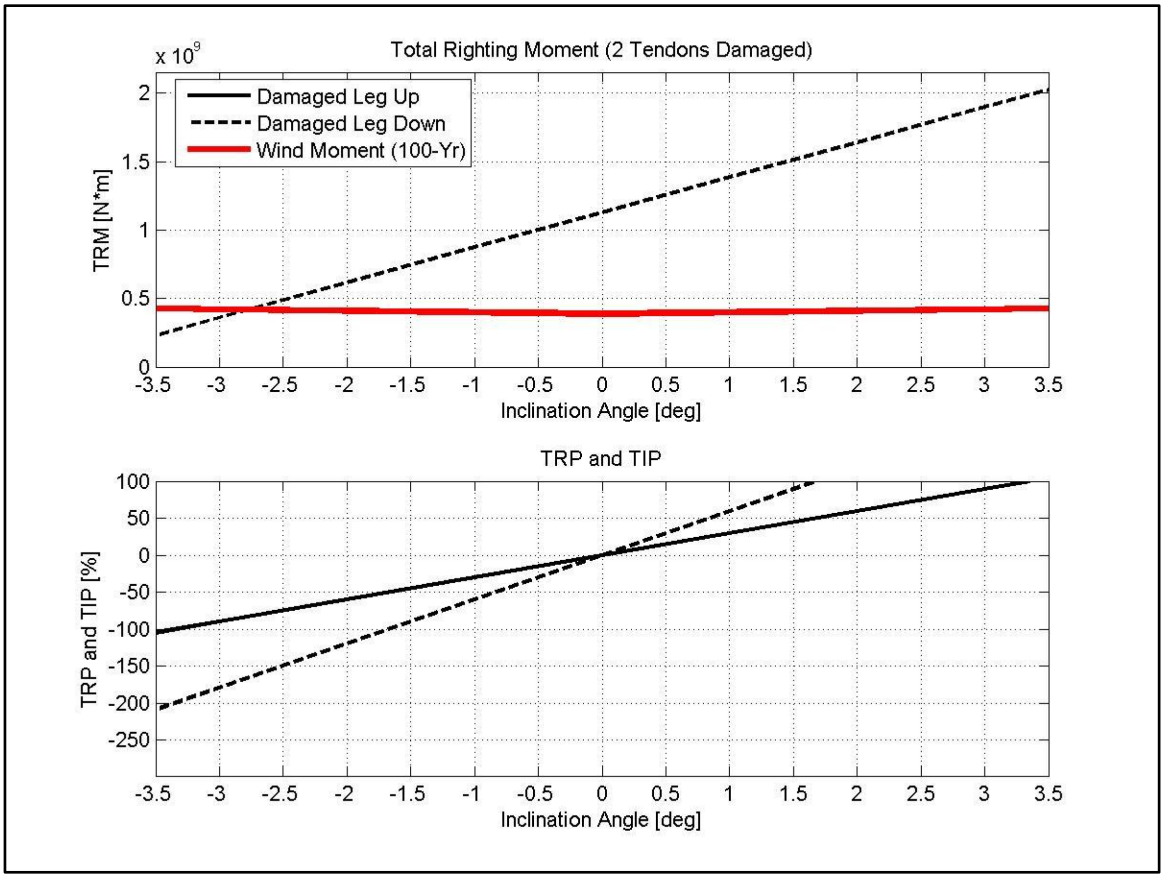


Figure 28. TRM of Moses TLP (2 tendon damaged)

Again, using similar method as for the other four-leg TLPs, we found SC of the Moses TLP to be 4.12 (due to buckling) and 2.32 (due to buckling) for intact case and 1 tendon damaged case, respectively. Similarly to the SeaStar TLP and the E-TLP, when both tendons in the same leg are damaged, SC becomes negative (due to yielding) and the hull will keep inclining until capsize occurs, due to its negative metacentric height, which will be explained shortly. Table 5 summarizes the results for the Moses TLP for all intact and damage cases. The critical angles in bold are the lower angles which we used to find TRM and SC.

Table 5. Summary of Moses TLP's intact and partially damaged stabilities

Cases (Diagonal)		M_wind (N*m)	Ta (N)	TTP_allowed (%)	φ_ini (deg)	(φ-φ_ini)_buckle (deg)	(φ-φ_ini)_yield (deg)	TRM (N*m)	SC	C1 (N*m)	C2_t (N*m/radian)	C2_b (N*m/radian)	Buoyancy contrib (%)	Buoyancy adj perc (%)
Intact		3.88E+08	8.20E+06	225	0	**1.7**	3.7	1.6E+09	**4.12**	0	5.78E+10	-4.57E+09	-7.3	0.00
1 damaged	Dmg leg up		9.37E+06	184	0.76	**1.5**	1.9	9.0E+08	**2.32**	-4.88E+08	4.13E+10	-4.57E+09	-10.0	0.21
	Dmg leg down				-0.76	2.5	4.8	1.6E+09	4.12	4.88E+08				
2 damaged	Dmg leg up		1.09E+07	145	4.40	-1.1	**-2.0**	Negative	**Negative**	-1.13E+09	1.93E+10	-4.57E+09	-19.2	0.48
	Dmg leg down				-4.40	6.1	9.6	N/A		1.13E+09				

Stability of Moses TLP with a Completely Damaged Tendon System

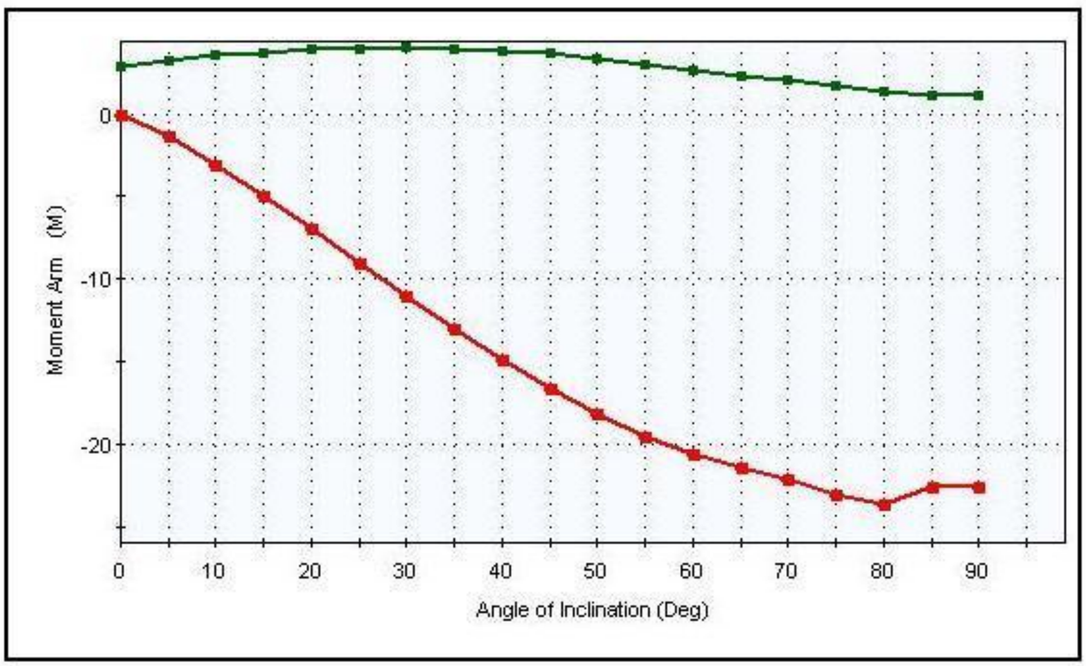


Figure 29. Floating stability curves of Moses TLP

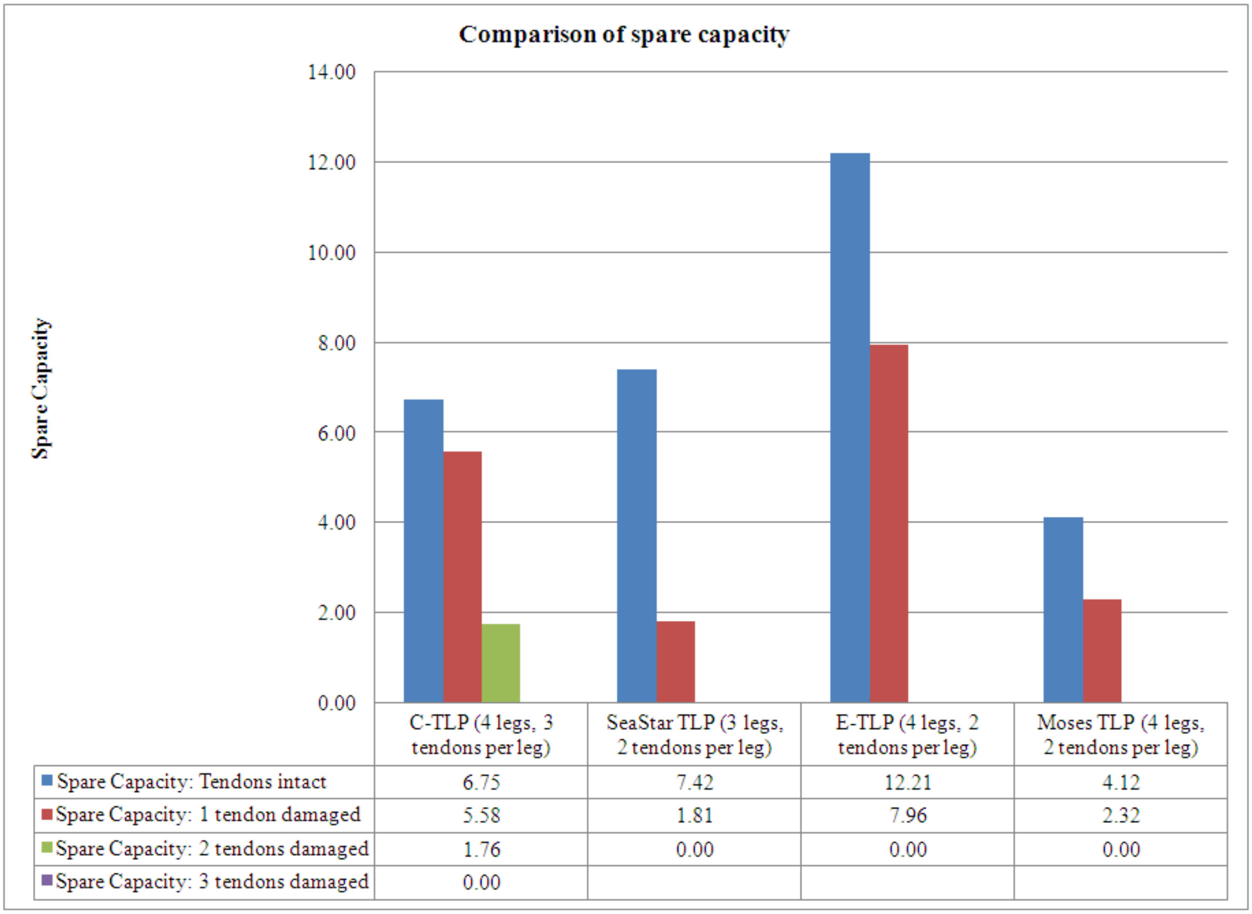
As shown in Figure 29, the righting arm becomes negative (i.e. center of gravity above metacenter) when the platform is inclined at a very small angle, the righting moment provided by the buoyancy and weight is negative. It is mainly due to its relatively small column separation which produces very limited water-plane area to contribute to hull stability. Therefore, at its freely floating draft of 14.2 m, the Moses TLP, in the same way of the other type of Mini-TLP (i.e. the SeaStar) is not able to float upright on its own due to its -30.7 m metacentric height, hence can be classified as unstable.

CHAPTER VI

SUMMARY AND CONCLUSION

Figure 30 summarizes the results of this study. When all tendons are intact and wind is the only source of upsetting moment, E-TLP has the best stability with a SC of 12.21, mainly due to its relatively small topside windage area resulting from the single deck topside design. In the case of one damaged tendon, E-TLP has a SC value of 7.96, a significant reduction from 12.21 but still highest among all four, again due to its single deck topside design. In the case two damaged tendons on the same tension leg, C-TLP has a SC value of 1.76, while that of the other three TLPs becomes negative (shown as 0.0 in the figure). It should be noted that the C-TLP has three tendons on each leg as opposed to only two tendons on each tension leg for the other three TLPs. When all three tendons are damaged, the SC of C-TLP also becomes negative just like the other three TLPs after losing all tendons one tension leg. In summary, when all tendons on one tension leg are lost, all remaining tendons on other tension legs will be damaged (buckling or yielding) and hence eventually lost. After all tendons are completely damaged, however, C-TLP and E-TLP still have sufficient static stability, satisfying the related requirements on the stability of a freely floating structure. On the other hand, once the Mini-TLPs lose all tendons, they will have negative metacentric height (GM) and cannot stay in upright position even without any upsetting moment, needless to say to survive 100-year wind upsetting moment.

As indicated by the percentage of the righting moment contributed from the buoyancy and weight of TLPs as shown in the previous Tables, buoyancy and weight make positive contribution to the stability in the case of the C-TLP and the E-TLP. This is mainly due to their relatively large column spacing and waterplane area. Their positive righting arms as a function of inclination angle prevent them from capsizing in case all of the tendons are lost. On the other hand, for mini-TLPs such as the SeaStar TLP and the Moses TLP, buoyancy and weight result in heeling moment (or negative righting moment) due to their negative metacentric heights (that is, the center gravity is above the metacenter). It should be noted that the assumption of the height of the gravity center equal to the draft made the center of gravity too high in the case of Moses TLP because of its extremely large draft (39.7 m). Hence, the related heeling moment resulted from the buoyancy and weight may be overestimated in comparison of that of the SeaStar TLP. However, the result for a negative metacenter height in the case of Moses TLP remains valid if the vertical position of its gravity center reduces to similar value as that of SeaStar TLP. A negative metacentric height indicates that the stability of a mini-TLP depends solely on its tendon system. Because of the negative metacenter height, once one tendon is damaged and lost, its static stability will be reduced more significantly in the case of a mini TLP than in the case of a large four-leg TLP.



	C-TLP (4 legs, 3 tendons per leg)	SeaStar TLP (3 legs, 2 tendons per leg)	E-TLP (4 legs, 2 tendons per leg)	Moses TLP (4 legs, 2 tendons per leg)
Spare Capacity: Tendons intact	6.75	7.42	12.21	4.12
Spare Capacity: 1 tendon damaged	5.58	1.81	7.96	2.32
Spare Capacity: 2 tendons damaged	1.76	0.00	0.00	0.00
Spare Capacity: 3 tendons damaged	0.00			

Figure 30. Comparison of spare capacity

Through this study, it is also found that there exist the most vulnerable or dangerous orientation of the rolling axis and hence wind headings for each type of TLPs from the view of the stability. For square shaped TLPs (i.e. C-TLP, E-TLP and Moses TLP), the most vulnerable rolling axes are coincident with or in a parallel to its diagonal. When the tendon system is intact, buckling in tendons on the down tension leg likely occurs before yielding of tendons on the up tension leg. In the cases that one or more tendons on a tension leg are damaged, the most dangerous wind direction is from the tension leg with a damaged tendon or tendons to the intact tension leg at the diagonally opposite corner. For an intact three-leg TLP such as SeaStar TLP, the worst case scenario is when the wind is blowing from the two leg side in the direction parallel with the single leg (pontoon), which may result in buckling of the tendons on the single leg. If one tendon has been damaged, the worst case scenario is when the wind is blowing from and in parallel with the leg of a damaged tendon, which may result in yielding of the remaining tendon on the damaged leg. This finding is of great importance should dynamic stability analysis on similar types of TLPs be performed in the future. Wind, wave and current headings can be chosen selectively to drastically reduce the cases of numerical simulation which usually are computationally intensive.

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APPENDIX

Appendix A: Proof of rolling axis independence for C-TLP

$$M = 3\left[T_0 + k\phi\left(\frac{Loa}{2}\cos\theta\,(1+\tan\theta)\right)^2\right] + 3\left[T_0 + k\phi\left(\frac{Loa}{2}\cos\theta\,(1-\tan\theta)\right)^2\right] - 3\left[T_0 - k\phi\left(\frac{Loa}{2}\cos\theta\,(1+\tan\theta)\right)^2\right] - 3\left[T_0 - k\phi\left(\frac{Loa}{2}\cos\theta\,(1-\tan\theta)\right)^2\right]$$

θ is the angle between the rotated rolling axis and the original strict tilt rolling axis. The T_0 terms and θ terms are cancelled out in this equation, resulting in the following equation for tendon righting moment that is independent of θ.

$$M = 3k\phi Loa^2$$

Appendix B: Theory of initial stability

A floating body reaches equilibrium when its weight is equal to the buoyancy and the line of action of these two forces is collinear. It is considered stable equilibrium if a floating body is slightly displaced from its equilibrium position and returns to that position by the buoyancy force. Righting moment exists at any angle of inclination where the forces of weight and buoyancy act as a couple to move the body toward the upright position. Static stability involves the magnitude of the righting moment applied to the floating body at certain inclination angle and a given draft. Initial stability computes the righting moment at small angle of inclination where trigonometric functions can be linearized, while large angle stability computes the righting moments at larger angle of inclination, up to the point that the floating body loses its stability.

Equations used by StabCAD for the hydrostatic and stability curves applied to the C-TLP are shown below (Tupper, 2004):

$$\nabla = 4[(L \times w \times h) + (\pi R^2)T]$$

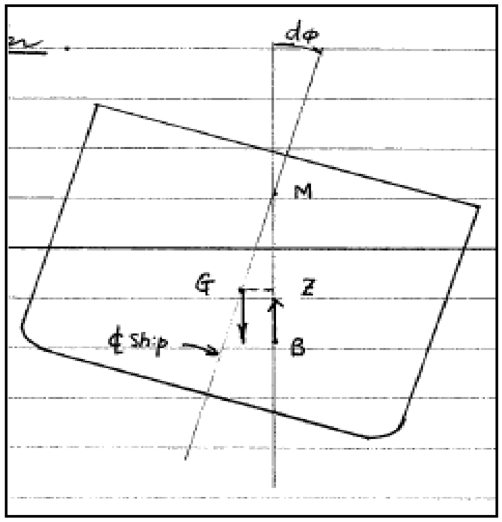
$$KB = \frac{\sum(\nabla_{unit}\, VCB_{unit})}{\nabla} = \frac{4\left[(L \times w \times h)\left(\frac{h}{2}\right) + (\pi R^2)T\left(\frac{T}{2}\right)\right]}{\nabla}$$

$$I_x = \int y^2\, dA_w + Ad^2 = 4\left[\frac{\pi R^4}{4} + (\pi R^2)\left(\frac{LOA}{2} - R\right)^2\right]$$

$$BM = \frac{I_x}{\nabla}$$

$$GM = KB + BM - KG$$

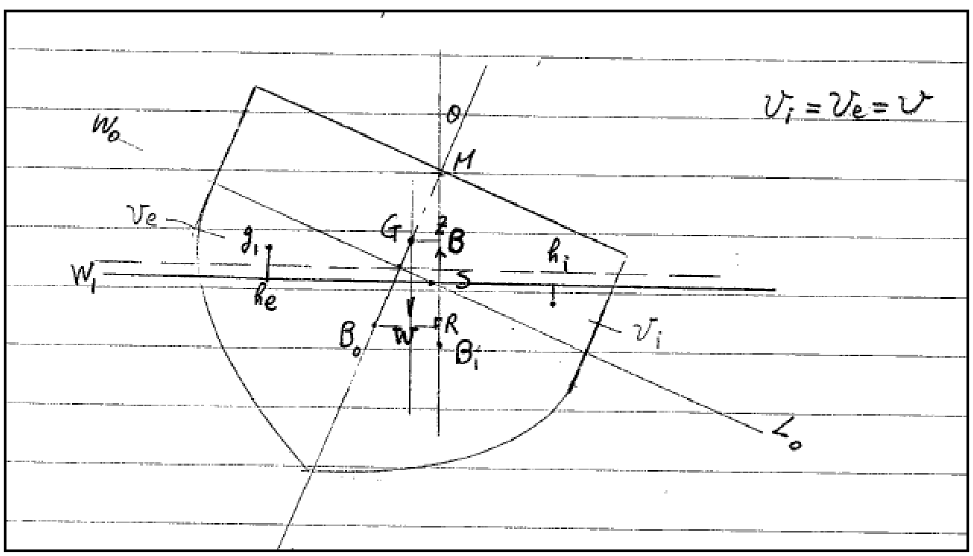
$$GZ = GMd\phi$$



The value of metacentric height, GM, is regarded as a constant when ϕ is smaller than 5°. A floating body is considered stable when GM is positive.

Appendix C: Theory of large angle stability

While the metacentric height GM is a measure of initial stability, it can no longer be regarded as a fixed point relative to the platform when the inclination angle exceeds 5°. Therefore, the metacentric height is no longer a suitable criterion for measuring the stability of a floating body. Instead, righting arm GZ is used for large angle stability calculations. The below figure and equations demonstrate how GZ value is computed. As shown in the below figure, rolling axis of a ship shaped floating body moves away from the plane of longitudinal symmetry. The expression for GZ in initial stability no longer holds in large angle stability.



Instead, a different expression is derived for large angle stability, as shown below.

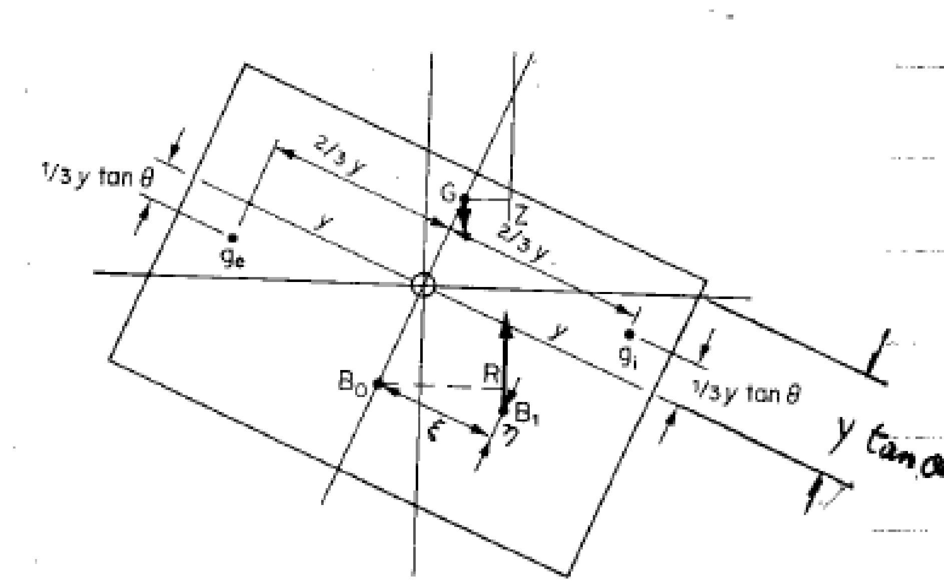


Figure 5.26

$$\xi = TCB' - TCB = \frac{\sum(\nabla_{unit}\, TCB_{unit})}{\nabla} - TCB$$

$$\eta = VCB' - VCB = \frac{\sum(\nabla_{unit}\, VCB_{unit})}{\nabla} - VCB$$

$$BR = \xi \cos\phi + \eta \sin\phi$$

$$GZ = BR - BG \sin\phi$$

Appendix D: Equations for verification of StabCAD output

To verificate the GZ outputs for the C-TLP in various circumstances computed by StabCAD, the following equations were used in order to determine ξ *and* η :

Fully submerged Columns

$$M_{col,V} = \nabla_{col} VCB_{col} = \pi R^2 T \left(\frac{T}{2}\right)$$

$$M_{col,T} = \nabla_{col} TCB_{col} = \pi R^2 T \left[\pm\left(\frac{LOA}{2} - R\right)\right]$$

Partially submerged Columns

$$M_{col,V} = \nabla_{col} VCB_{col} = \pi R^2 \left[T \pm \left(\frac{LOA}{2} - R\right)\tan\phi\right] \frac{\left[T \pm \left(\frac{LOA}{2} - R\right)\tan\phi\right]}{2}$$

$$M_{col,T} = \nabla_{col} TCB_{col} = \pi R^2 \left[T \pm \left(\frac{LOA}{2} - R\right)\tan\phi\right]\left[\pm\left(\frac{LOA}{2} - R\right)\right]$$

Fully submerged Forward and Aft Pontoon

$$M_{FAP,V} = \nabla_{FAP} VCB_{FAP} = 2(L \times w \times h)\left(\frac{h}{2}\right)$$

$$M_{FAP,T} = \nabla_{FAP} TCB_{FAP} = 2(L \times w \times h)(0)$$

Partially submerged Forward and Aft Pontoon

$$M_{FAP,V} = \nabla_{FAP} VCB_{FAP} = 2(L \times w \times h)\left(\frac{h}{2}\right)$$

$$M_{FAP,T} = \nabla_{FAP} TCB_{FAP} = 2(L \times w \times h)\left[\frac{L}{2} - \left(\frac{L}{2} + \frac{T - \frac{h}{2}}{\tan\phi}\right)\right]$$

Fully submerged Port Pontoon

$$M_{PP,V} = \nabla_{PP} VCB_{PP} = (L \times w \times h)\left(-\frac{h}{2}\right)$$

$$M_{PP,T} = \nabla_{PP} VCB_{PP} = (L \times w \times h)\left[-\left(\frac{LOA}{2} - \frac{W}{2}\right)\right]$$

Fully submerged Starboard Pontoon

$$M_{SBP,V} = \nabla_{SBP} VCB_{SBP} = (L \times w \times h)\left(\frac{h}{2}\right)$$

$$M_{SBP,T} = \nabla_{SBP} VCB_{SBP} = (L \times w \times h)\left(\frac{LOA}{2} - \frac{W}{2}\right)$$

Hand calculation has been made at several locations using the above equations to verify the GZ output from StabCAD.

Submerged Volume:		Y	Z	M_y	M_z
2 Port Columns Vol.	12384	-30.0	9.9	-371528	122048
2 Starboard Columns Vol.	19032	30.0	15.1	570949	288233
Port Pontoon Vol.	3450	-32.5	2.5	-112125	8625
Starboard Pontoon Vol.	3450	32.5	2.5	112125	8625
2 (Fore & Aft) Pontoon Vol.	6900	0.0	2.5	0	17250
Displacement in Volume:	45216	GZ from StabCAD = 0.96	Sum:	199421	444781
Draft(m)	25		ZB	4.4	9.8
Heel Angle [degrees]	10		KB	0.0	9.4
[radians]	0.17			ξ	η
Single Pontoon Block Vol.	3450		Diff	4.4	0.4
BR	4.41	StabCAD GZ output verification			
Correction Factor	0.03				
GZ	**0.97**				

Hand GZ calculation at Draft = 25m, Heel Angle = 10 degrees.

Submerged Volume:		Y	Z	M_y	M_z
2 Port Columns Vol.	8847	-30.0	7.0	-265419	62289
2 Starboard Columns Vol.	22569	30.0	18.0	677059	405323
Port Pontoon Vol.	3450	-32.5	2.5	-112125	8625
Starboard Pontoon Vol.	3450	32.5	2.5	112125	8625
2 (Fore & Aft) Pontoon Vol.	6900	0.0	2.5	0	17250
Displacement in Volume:	45216	GZ from StabCAD = 2.35	Sum:	411641	502112
Draft(m)	25		ZB	9.1	11.1
Heel Angle [degrees]	20		KB	0.0	9.4
[radians]	0.35			ξ	η
Single Pontoon Block Vol.	3450		Diff	9.1	1.7
BR	9.12	StabCAD GZ output verification			
Correction Factor	0.03				
GZ	**2.37**				

Hand GZ calculation at Draft = 25m, Heel Angle = 20 degrees.

Submerged Volume:		Y	Z	M_y	M_z
2 Port Columns Vol.	4825	-30.0	3.8	-144755	18527
2 Starboard Columns Vol.	26591	30.0	21.2	797723	562667
Port Pontoon Vol.	3450	-32.5	2.5	-112125	8625
Starboard Pontoon Vol.	3450	32.5	2.5	112125	8625
2 (Fore & Aft) Pontoon Vol.	6900	0.0	2.5	0	17250
Displacement in Volume:	45216	GZ from StabCAD = 4.82	Sum:	652968	615695
Draft(m)	25		ZB	14.4	13.6
Heel Angle [degrees]	30		KB	0.0	9.4
[radians]	0.52			ξ	η
Single Pontoon Block Vol.	3450		Diff	14.4	4.2
BR	14.59	StabCAD GZ output verification			
Correction Factor	0.03				
GZ	**4.75**				

Hand GZ calculation at Draft = 25m, Heel Angle = 30 degrees.

Draft(M)	10 degrees	20 degrees	30 degrees	40 degrees	50 degrees	60 degrees
25	0.96	2.35	4.82	8.57	5.59	1.38

StabCAD GZ output at Draft = 25 m

Appendix E: Input files for StabCAD

Geometry BETA file for C-TLP:

```
ALPID 3D VIEW                 0.832 0.555    -0.148 0.222 0.964   1
ALPID GLOBAL XY PL    0.   0.   0.   1.   0.   0.   0.   1.   0.   1
ALPID Global YZ Pl    0.   0.   0.   0.   0.   1.   0.   1.   0.   1
ALPID Global XZ Pl    0.   0.   0.   1.   0.   0.   0.   0.   1.   1
ALPREF 3D View        0.  0.  0.  ON          0.50            G   1

 -----------------------------------------------------------------------------
 Conventional TLP Model (Geometry)
 Created by Ning Xu
 Last modified: April 07, 2008
 -----------------------------------------------------------------------------
 Golobal Origin
JOINT 1000   0.000  0.000  0.000
 Topside Block
JOINT  103     40.    40.    51.
JOINT  203    -40.    40.    51.
JOINT  303     40.   -40.    51.
JOINT  403    -40.   -40.    51.
JOINT  104     40.    40.    76.
JOINT  204    -40.    40.    76.
JOINT  304     40.   -40.    76.
JOINT  404    -40.   -40.    76.
 Derricks
JOINT  001      0.     0.    76.
JOINT  002      0.     0.   126.
JOINT  003     40.     0.    51.
JOINT  004     90.     0.   111.
 Four Corners
JOINT  101  30.000 30.000  0.000
JOINT  102  30.000 30.000 51.000
JOINT  201 -30.000 30.000  0.000
JOINT  202 -30.000 30.000 51.000
JOINT  301  30.000-30.000  0.000
JOINT  302  30.000-30.000 51.000
JOINT  401 -30.000-30.000  0.000
JOINT  402 -30.000-30.000 51.000
 Port
JOINT  501  23.000 22.500  0.000
JOINT  502  23.000 37.500  0.000
JOINT  503 -23.000 37.500  0.000
JOINT  504 -23.000 22.500  0.000
JOINT  505  23.000 22.500  5.000
JOINT  506  23.000 37.500  5.000
JOINT  507 -23.000 37.500  5.000
JOINT  508 -23.000 22.500  5.000
 Starboard
JOINT  601  23.000-37.500  0.000
JOINT  602  23.000-22.500  0.000
JOINT  603 -23.000-22.500  0.000
JOINT  604 -23.000-37.500  0.000
JOINT  605  23.000-37.500  5.000
JOINT  606  23.000-22.500  5.000
JOINT  607 -23.000-22.500  5.000
JOINT  608 -23.000-37.500  5.000
 Fore
JOINT  701  22.500 23.000  0.000
JOINT  702  37.500 23.000  0.000
JOINT  703  37.500-23.000  0.000
JOINT  704  22.500-23.000  0.000
```

```
JOINT  705  22.500 23.000  5.000
JOINT  706  37.500 23.000  5.000
JOINT  707  37.500-23.000  5.000
JOINT  708  22.500-23.000  5.000
 Aft
JOINT  801 -37.500 23.000  0.000
JOINT  802 -22.500 23.000  0.000
JOINT  803 -22.500-23.000  0.000
JOINT  804 -37.500-23.000  0.000
JOINT  805 -37.500 23.000  5.000
JOINT  806 -22.500 23.000  5.000
JOINT  807 -22.500-23.000  5.000
JOINT  808 -37.500-23.000  5.000
 Topside Block
PANEL    D       TOP  103  203  403  303
PANEL    D       TOP  104  304  404  204
PANEL    D       TOP  103  303  304  104
PANEL    D       TOP  204  404  403  203
PANEL    D       TOP  303  403  404  304
PANEL    D       TOP  103  104  204  203
 Derricks
CYLIND   W       TOP  001  002    10.
CYLIND   W       TOP  003  004     4.
 Port Pontoon
PANEL           PON  505  501  504  508
PANEL           PON  502  506  507  503
PANEL           PON  503  507  508  504
PANEL           PON  505  506  502  501
PANEL           PON  506  505  508  507
PANEL           PON  501  502  503  504
 Starboard Pontoon
PANEL           PON  605  601  604  608
PANEL           PON  602  606  607  603
PANEL           PON  603  607  608  604
PANEL           PON  605  606  602  601
PANEL           PON  606  605  608  607
PANEL           PON  601  602  603  604
 Fore Pontoon
PANEL           PON  703  704  708  707
PANEL           PON  701  702  706  705
PANEL           PON  704  701  705  708
PANEL           PON  702  703  707  706
PANEL           PON  705  706  707  708
PANEL           PON  702  701  704  703
 Aft Pontoon
PANEL           PON  803  804  808  807
PANEL           PON  801  802  806  805
PANEL           PON  804  801  805  808
PANEL           PON  802  803  807  806
PANEL           PON  805  806  807  808
PANEL           PON  802  801  804  803
 Columns
CYLIND          COL  101  102 20.000
CYLIND          COL  201  202 20.000
CYLIND          COL  301  302 20.000
CYLIND          COL  401  402 20.000

END
```

Configuration BETA file for C-TLP:

```
--------------------------------------------------------------------------------
 Conventional TLP Model (HHYDROSTATICS AND INTACT STABILITY)
 Created by Ning Xu
 Last modified: April 07, 2008
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 Input Parameters
STBOPT                EQ CALC ME ME       PTPTPT
CFORM        15.   27.5    2.5     0.     0.
INTACT        0.    60.     5.
DRAFT           49623.     0.     0.   27.5    45. PROG USER
DRAFT           33112.     0.     0.   27.5    45. PROG USER
KGPAR       55.6   50.1          1.4
 Take GEOM File
FILEIN    E:\STABCAD\CONVENTIONAL\GEOM
```

VITA

Ning Xu was born on November 2, 1982 in Tianjin, China. He received his Bachelor of Science degree in ocean engineering from Texas A&M University in December 2006 and continued his study in the ocean engineering program at Texas A&M University in January 2007 to pursue a Master of Science degree. His research interests are static stabilities of column stabilized offshore floating structures with a focus on Tension Leg Platforms. He currently works in the offshore oil and gas industry in Houston, Texas.

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