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Title:

ClubStead Preliminary Analysis:
Structural Design

Client:
The SeaStead Institute

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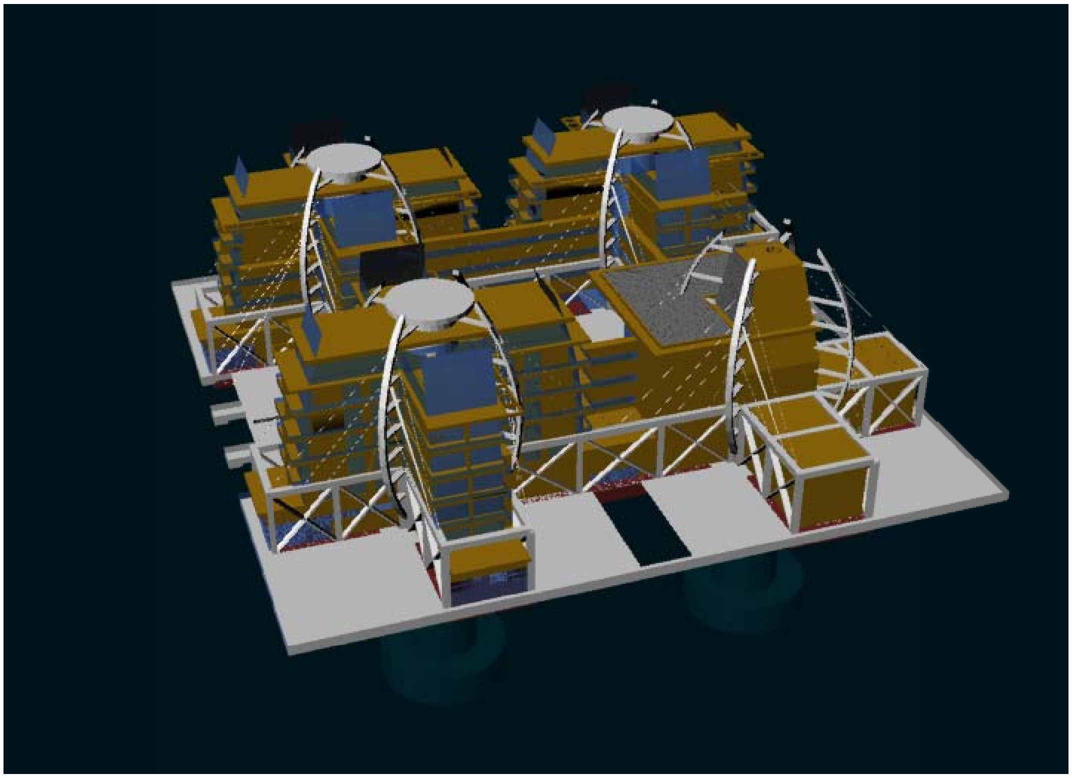
ClubStead Preliminary Analysis: Structural Design



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1. Summary and Conclusions

The structural analysis of the ClubStead primary objective is the sizing of the primary deck structure. As a result, the overall weight of primary steel necessary to support the payload on the ClubStead is determined. Table 1 summarizes the main contributions to the weight of the primary deck structure. A 10% increase in weight is added to account for the detail elements such as the connection between the columns and the trusses.

Table 1; Weight element summary

Description	Number per ClubStead	Weight per element (st)	Total Weight (st)
Main truss between columns	4	286.3	1145.1
Cantilevered truss	8	49.6	396.6
Corner open surface area	4	9.3	37.4
Side open surface area	4	29.5	117.9
Center open surface area	1	40.7	40.7
Towers	4	88.2	352.8
Cables	96	0.8	76.3
Vertical pipes for cable support	16	11.5	184.7
	TOTAL	515.8	**2351.4**
	Contingency (10%)		**235.1**

The sizing of individual cables is based on a minimum safety factor of 10 between the static tension and the minimum breaking load. The effects of wave and wind dynamics on the design of the cables need to be examined thoroughly. The design of the anchorage system, which may include a damping structure, should also be considered in the detail design analysis.

The submerged columns and footings, which provide the hydrodynamic stability to the structure, are designed according to the American Bureau of Shipping (ABS) rules. The weight of the columns and footings is determined based on volumetric ratios with similar projects. It is assumed that ring stiffeners and small T-shaped stiffeners are used to strengthen the columns.

2. Introduction

This structural analysis is part of the design of the ClubStead. It is performed to size the main structural elements of the ClubStead and to understand the weight requirements. The analysis is run for the largest loads the platform could see, which happen in the most extreme waves. The structural layout of the columns is performed as well to better define the weight requirements.
This document focuses on the strength analysis of the ClubStead upper structure. Fatigue design was not part of the scope of this preliminary analysis, because it will only affect the connections between structural elements.

Extreme loads on the platform consist of wave loads combined with the dead weight of the buildings and living areas. Trusses and cable supported beams are made of A572 Grade 50 steel to withstand such loads. The API recommendation for offshore platforms is used to verify the buckling and strength ratio on the individual beams. Results, including the type of beams used for each part of the deck, are described herein.

3. Methodology

3.1. Design Criteria

The design of the truss is based on Section 3 – Structural Steel Design of API Recommended Practice 2A-WSD [1].

For cylindrical members, API defines allowable axial, bending shear and hoop stresses. These allowable stresses should be compared to the maximum stresses predicted by the analysis. The overall structural reliability of a member is estimated by computing ratios that combine the maximum to allowable stress ratios with appropriate safety factors [1]. All computed ratios must be less than 1.0 to comply with API RP2A-WSD.

API RP2A-WSD provides allowable stresses for:

- The tensile stress
- The axial compressive stress
- The bending stress
- The shear stress

These allowable values are based on member properties such as yield strength of the material, inertia, length and diameter. Relevant combined ratios of axial compression and bending and of axial tension and bending are computed according to API RP2A-WSD.

3.2.Finite-Element Model

A finite-element model is built in SAP2000 v12. The primary structure, including the submerged columns and the truss on the deck, is represented with frame element. Frame elements in SAP2000 v12 are analyzed with beam theory. Buildings are modeled with area elements.

Loads on the platform include:

- Dead loads: the weight of the buildings on the primary deck structure is applied by assigning a distributed load on the surface areas. The self-weight of the steel frame elements is added automatically.
- Wave loads: The wave force acting on the submerged frame element is calculated using Morison's equation, based on a linear Airy wave potential, defined in the next section. The wave loads are applied as distributed forces on the portion of the structure that is below the wave surface. Buoyant forces are calculated; they consist of concentrated forces at each end of a submerged frame object.
- Wind loads, propulsion loads and other secondary forces are neglected in this preliminary analysis. Their effect on the overall design of the deck structure is not relevant at this stage of design. Wind vibration on the deck should be the object of a specific detailed

analysis to ensure the vibration modes of the deck and cables are not excited by the turbulence in the wind.

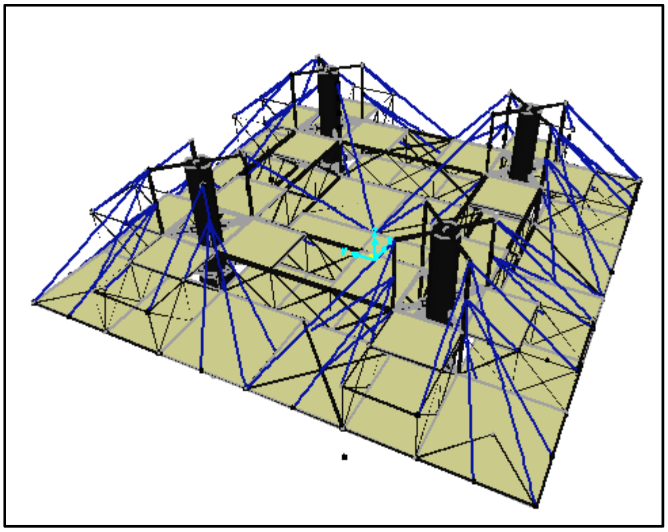

Figure 1: SAP2000 Model of the ClubStead

Extreme load cases are the ones which generate the worst possible loads on the truss. A quasi-static analysis is run on each wave loading case to obtain the local forces and moments on each element.
For each loading case, the stresses in the elements are computed based on a beam-column formulation which includes the effect of biaxial bending, torsion, axial deformation and biaxial shear deformations. [2]

Cable loads are applied using tendon elements. The pretension on the cables is set so the moment due to the cable counterbalances the moment due to the structural weight. Tendons are multi-strand cables, made of 270 ksi steel. The properties of the strands are listed in Table 2.

Table 2: Properties of the tendons to support the Cantilevered Truss

Property	Value	Unit
Nominal diameter	0.5	in
Nominal area	0.153	in2
Nominal weight/mass	0.53	lb/ft
Tensile strength	270	ksi
Min. breaking load	41.3	kips
Young's modulus	28500	ksi

On the tower, the cables may be anchored directly to the support beams on the column. Alternatively, the anchors might be fixed on an external beam, which is itself welded or bolted to the support beams of the columns, as shown in Figure 2. In the SAP2000 model, the latter solution is investigated.

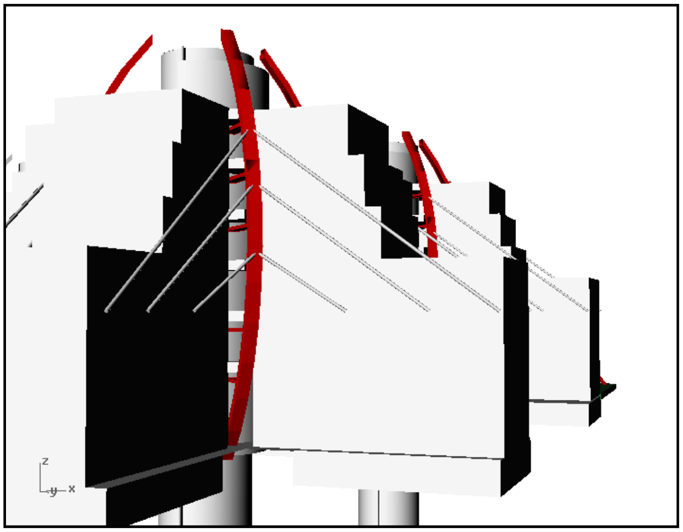

Figure 2: External beam for anchorage of cables (in red)

The detailed analysis of the cable loads subject to dynamic excitations is out of the scope of this study. A damping system may be necessary to counter the dynamic effects of wind and wave loads. This will be addressed in later design stages.

The design of the beam structure is carried out to minimize the weight while ensuring all API design ratios remain under 1.

3.3. Selection of Design Wave and Loads

The ClubStead is designed to withstand harsh weather conditions while dynamically positioned off the coast of San Diego, CA. The 100 year storm on site has a significant wave height of 27.2ft.

Such waves generate large loads on the columns. When the wavelength is such that the wave loads differ from one column to the other, the loads are transferred through the primary structure that connects the columns together.

In SAP2000, the wave loads are modeled using linear Airy wave theory, which assumes the ratio of wave amplitude to wave length is small. The wave loads on the structure are highest when the wavelength is equal to twice the distance between columns. These create the hogging and sagging structural modes. For 0 degree heading waves, this corresponds to a wave with a wavelength of 400ft. At 45 degree, the largest loads will occur for wavelengths of 566 and 283ft.

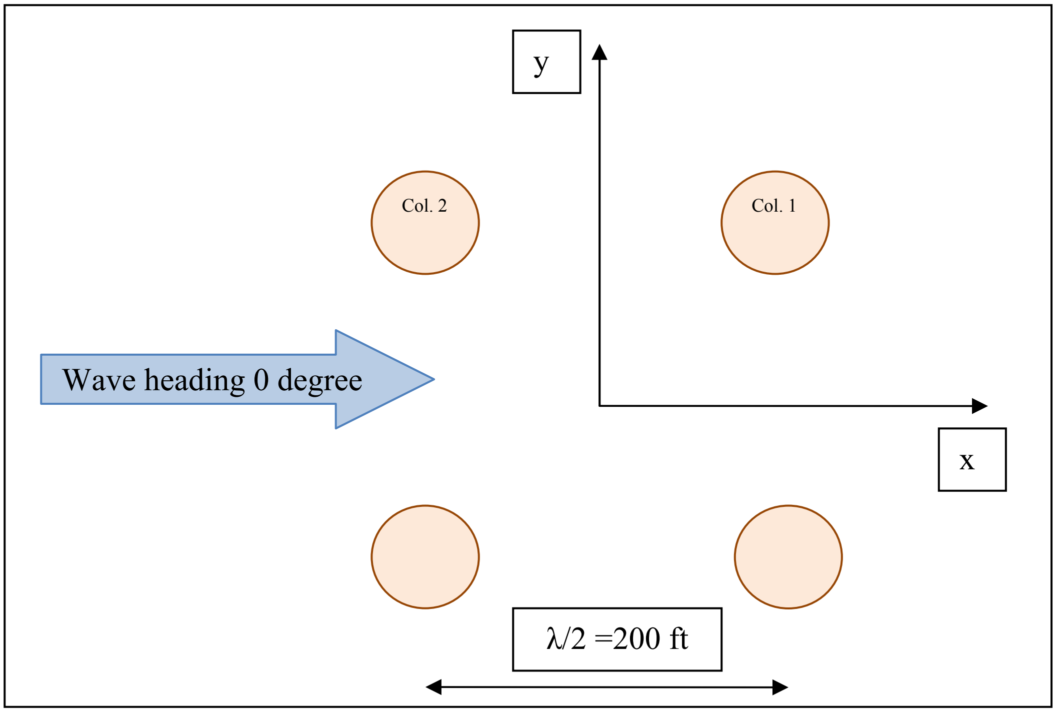

Figure 3: Definition of Relevant Design Wavelength for 0 deg. Heading Waves

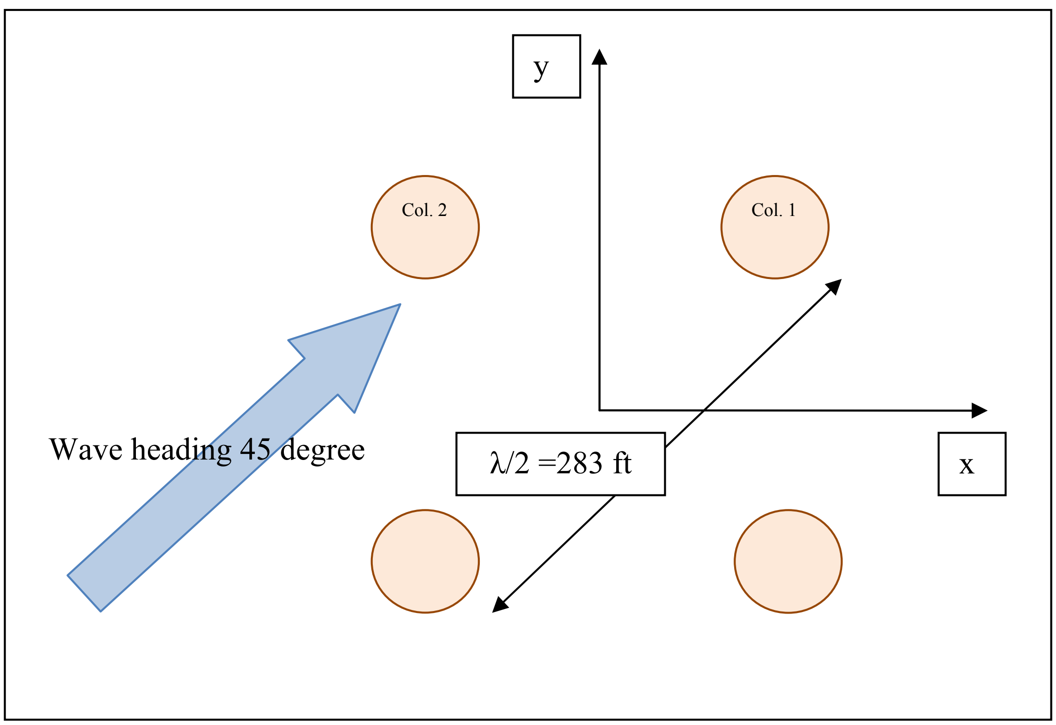

Figure 4: Definition of Relevant Design Wavelength for 45 deg. Heading Waves

In deep water, such wavelengths are associated with waves of periods between 7.4 and 10.5 seconds, as prescribed by the relation:

$$T = \sqrt{\frac{2\pi\lambda}{g}}$$, where λ is the wavelength and T the period of the wave.

Added mass and drag coefficients are assigned to the columns according to API recommendations.

The amplitude of the wave is chosen to represent the most extreme wave loads associated with the relevant wavelength at the location off the coast of San Diego, CA.
The table below summarizes the properties of linear waves considered in the structural analysis.

Table 3: Wave Parameters for Structural Analysis

Wave Type	Wavelength (ft)	Wave Direction (deg)	Wave Period (sec)	Wave Height (double amplitude) (ft)
Linear Airy	565.7	45.0	10.5	45
Linear Airy	282.8	45.0	7.4	35
Linear Airy	400.0	0.0	8.8	35

For each wave load, a multi-step static analysis is run with SAP2000 to obtain forces on the truss at all time steps of a period. The configurations that lead to the largest structural loads are chosen to carry out the design of the truss. The two wave configurations that yield the largest loads at 0 degree heading waves are represented below.

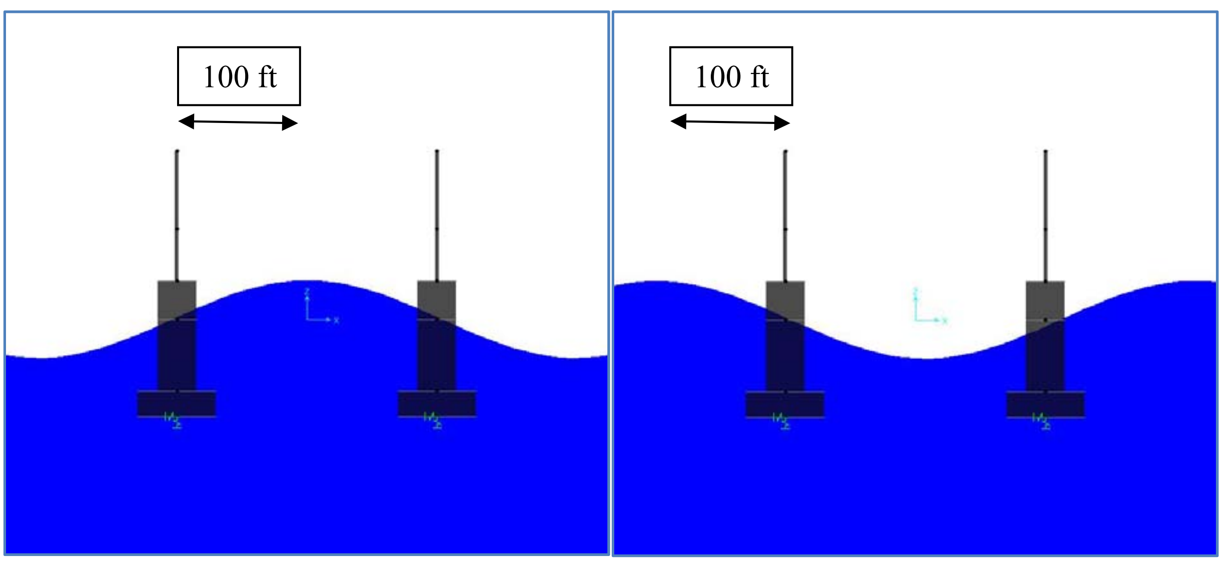

Figure 5: Maximum Wave Loads at 0 degree Heading, Hogging and Sagging Modes

4. Results of Finite-Element Analysis on Primary Deck Structure

4.1. Main Truss

The main truss is designed to support the buildings on the deck and connect the columns to each other. On top of supporting the overall weight of buildings, the truss must be able to withstand the wave load differential between two adjacent columns.

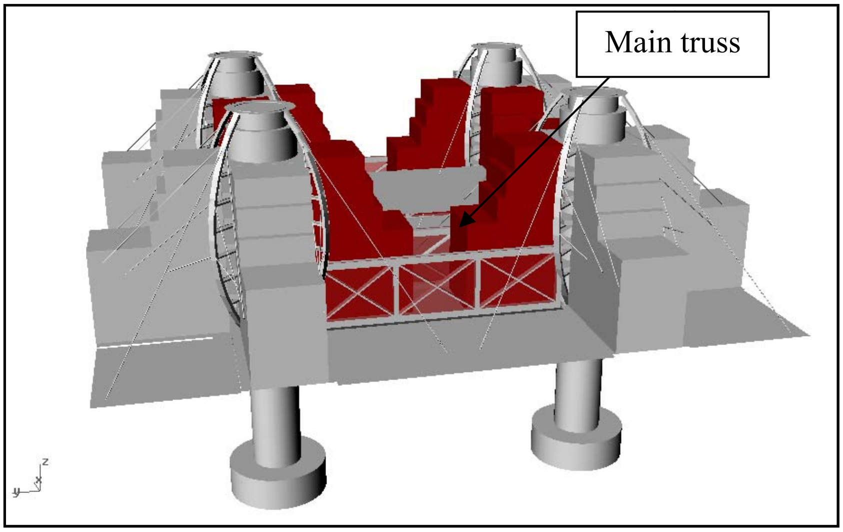

Figure 6: Main truss on ClubStead

The truss is 150ft long, 40ft high and 50ft wide; it encloses the two first floors of the buildings. The truss has 3 bays with diagonal beams to help support the weight and axial forces on the horizontal beams.

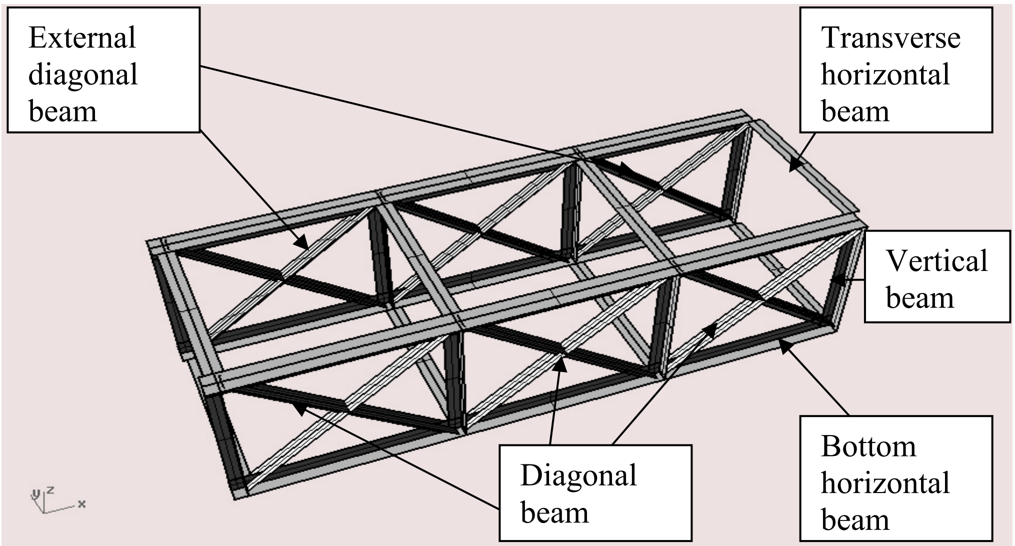

Figure 7: Perspective View of the truss between columns.

I-Beams, 2L corner beams and pipes configurations were analyzed in the optimization of the weight of the truss. In each case the size of the beams was minimized while meeting the maximum stress criteria from API. Due to the bending moments on the truss, pipes were the better choice. The optimized configuration is shown in Table 4.

Table 4: Design Summary of Optimized Truss Structure

Component	Number per truss	Type of beam	Name	unit length (ft)	unit weight (kips)	weight per truss (kips)	total weight (kips)
Horizontal Beam - Bottom	2	PIPE	PIPE48x1.4	150	104.6	209.2	836.9
Horizontal Beam - Top	2	PIPE	PIPE48x1	151	75.9	151.7	606.9
Diagonal Beam - external	4	PIPE	PIPE24x1	64.0	19.0	75.8	303.3
Diagonal Beam - others	8	PIPE	PIPE18x1	64.0	14.0	112.1	448.4
Vertical Beam	8	PIPE	PIPE8SCH40	40	1.1	8.5	34.2
Transverse Horizontal Beam	8	PIPE	PIPE10SCH40	50	1.9	15.1	60.4
						572.5	**2290.2**
						Total (st)	**1145.1**

Note that the name of the component includes its dimensions. For instance, a beam made of PIPE48x1.4 is a tubular beam with 48" (inches) outer diameter (4ft) and 1.4" wall thickness. Other notations refer to ANSI standards.

The following configuration was studied as a sensitivity to reduce the truss size.
Cables may be used to relieve the tension due to wave loads on the horizontal parts of the truss.
If cables with a pretension of 500 kips connect the tops of column as illustrated in Figure 8, the tension on the top beam is reduced by up to 20% compared to the case without cables. In such a case, a pipe of 1.5ft diameter and 1" wall thickness would be sufficient as the top horizontal beam.

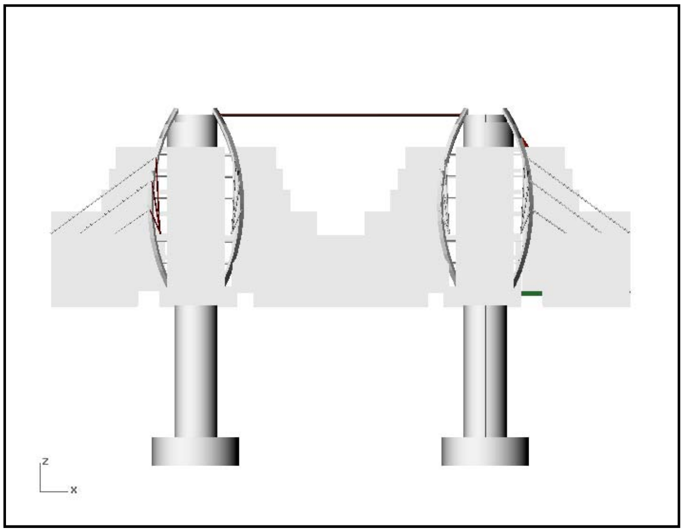

Figure 8: ClubStead model with Cables between Top of Towers

Alternatively, underwater cables or trusses may help relieve some weight of the truss. These configurations, shown in Figure 9, were not analyzed.

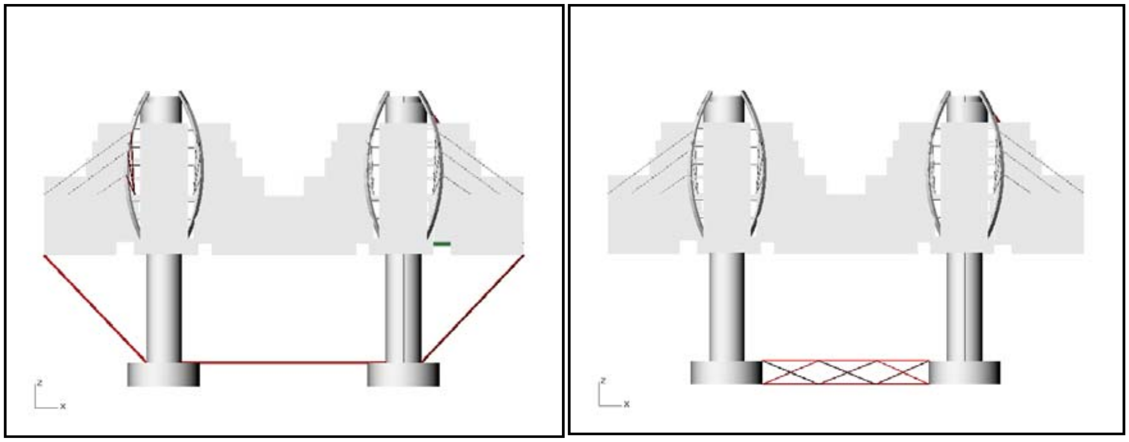

Figure 9: Alternative Lateral Support for Truss Structure

4.2.Truss for cantilevered buildings

The truss extends in the cantilevered buildings at the extremities of the platform (red in Figure 10). It partially supports the buildings. To minimize its weight, it is supported by tendons anchored on the vertical arches attached to the tower. Two tendons are used on each side of the building. A pretension ranging between 50 and 100 kips is applied to the tendons to counter the bending moment due to weight.

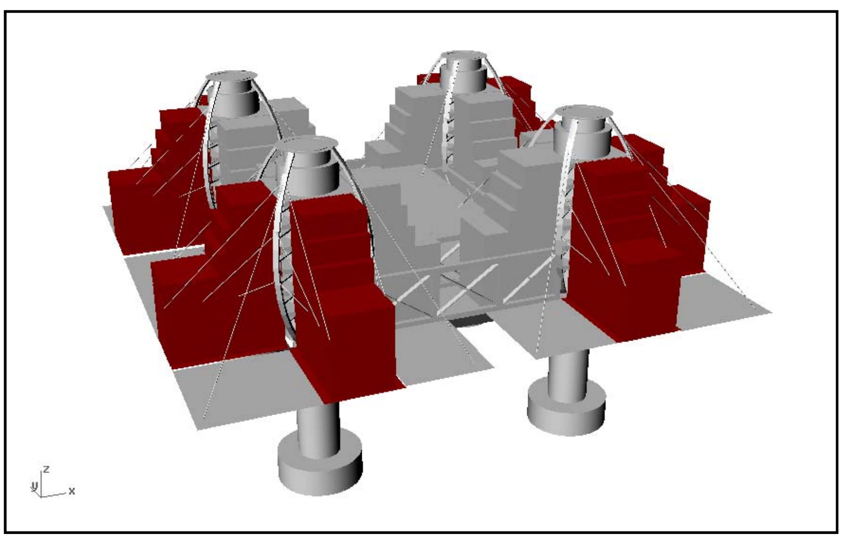

Figure 10: Cantilevered Buildings at the extremities of the ClubStead

The truss (

Figure 11) is 75ft long, 40ft high and 50ft wide. The characteristics of the optimized truss are summarized in Table 5.

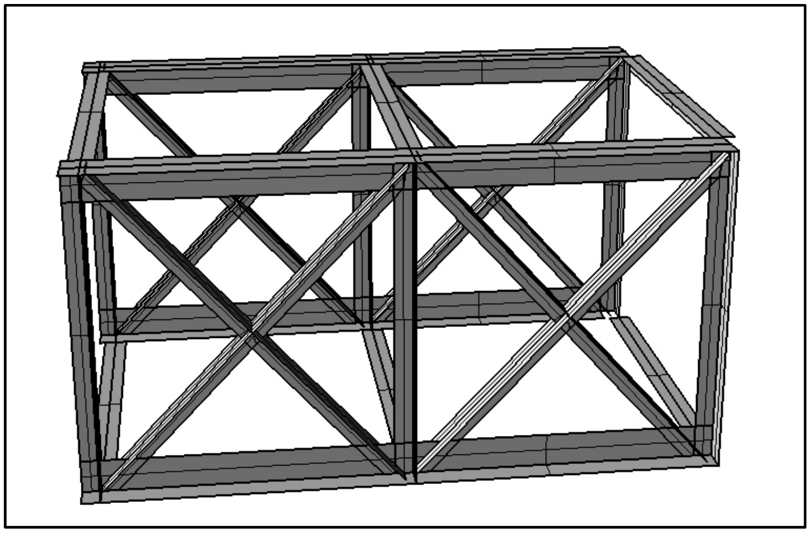

Figure 11: View of Cantilevered Truss

Table 5: Weight Summary and Configuration of Cantilevered Truss

Component	Number per truss	Type of beam	Name	cross section (ft2)	linear weight (kips per ft)	unit length (ft)	unit weight (kips)	weight per truss (kips)	total weight (kips)
Longitudinal Horizontal Beam	4	PIPE	PIPE18x5/8	0.237	0.118	75	8.82	35.3	282.2
Diagonal Beam - exterior	2	PIPE	PIPE18x1	0.371	0.182	54.8	9.96	19.9	159.4
Diagonal Beam	6	PIPE	PIPE10SCH40	0.077	0.038	54.8	2.07	12.4	99.4
Vertical Beam	6	PIPE	PIPE6SCH40	0.036	0.018	40	0.71	4.3	34.1
Transverse Horizontal Beam	6	PIPE	PIPE18x1/2	0.185	0.091	50	4.54	27.3	218.1
								99.2	**793.2**
								Total (st)	**396.6**

4.3.Suspended Light-Weight Areas

Additional light weight surface areas are suspended off the tower at the corners and sides of the platform and at its center (Figure 12).

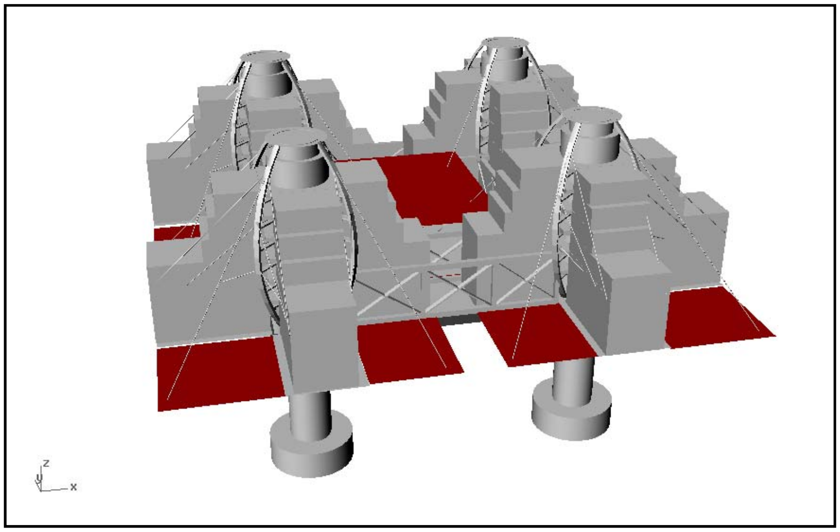

Figure 12: Lightweight Recreational Areas.

Cables are laid out symmetrically on all sides of the tower to balance the horizontal loads on the tower and cancel the overall bending moment. They are assigned pretensions of 10 kips or less. In the structural model, each 75x75ft square section is supported by 4 cables and diagonal beams, as illustrated in Figure 13.

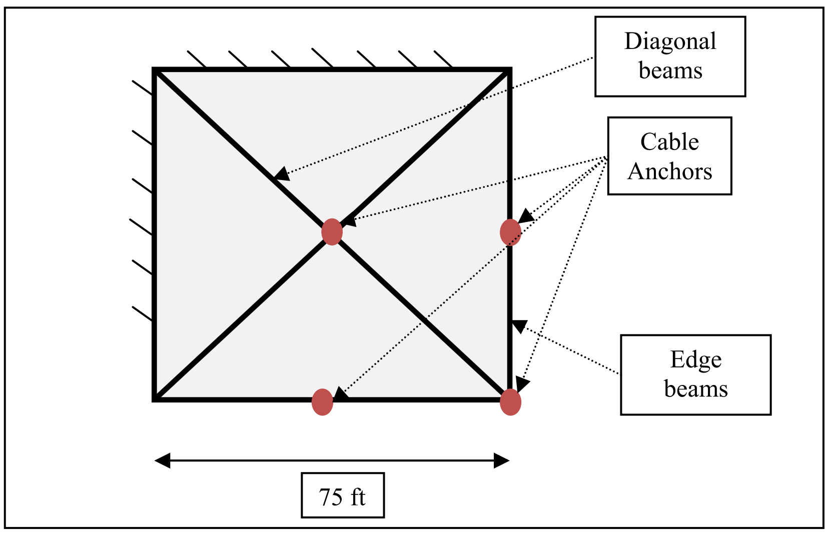

Figure 13: Layout of Cable Anchors and Support Beams on a 75ft by 75ft open surface area (top view).

The corner surface areas are supported by 2 edge beams and 2 diagonal beams as well as the side of the cantilevered truss. The sizing of the edge and diagonal beams is summarized in Table 6.

Table 6: Weight Summary of beams at corners of ClubStead

Component	Number per truss	Type of beam	Name	cross section (ft2)	linear weight (kips per ft)	unit length (ft)	unit weight (kips)	weight per truss (kips)	total weight (kips)
Edge	2	PIPE	PIPE18x1/8	0.049	0.024	75	1.79	3.6	14.3
Diagonal Beam	1	PIPE	PIPE24x11/16	0.350	0.171	53.0	9.1	9.1	36.3
Cross Beam	3	PIPE	PIPE10SCH40	0.077	0.038	159.1	6.0	6.0	24.0
								12.7	**74.7**
								Total (st)	**37.4**

The surface area at the center is similarly designed with tubular beams laid out diagonally and squarely between the main trusses. The weight is supported by cables suspended from the top of towers.

Table 7: Weight Summary of beams at Center of ClubStead

Component	Number per truss	Type of beam	Name	cross section (ft2)	linear weight (kips per ft)	unit length (ft)	unit weight (kips)	weight per truss (kips)	total weight (kips)
Edge	2	PIPE	PIPE18x1/2	0.191	0.094	150	14.0	28.1	28.1
Diagonal Beam	2	PIPE	PIPE24x1/2	0.256	0.126	212.1	26.6	53.3	53.3
Cross Beam	4	PIPE	PIPE10SCH40	0.077	0.038	212.1	8.0	32.1	32.1
								113.4	**113.4**
								Total (st)	**56.7**

The weight of the rectangular surface areas on the sides of the ClubStead between cantilevered trusses is described in Table 8.

Table 8: Weight Summary of beams on the sides of ClubStead

Component	Number per truss	Type of beam	Name	cross section (ft2)	linear weight (kips per ft)	unit length (ft)	unit weight (kips)	weight per truss (kips)	total weight (kips)
Edge	1	PIPE	PIPE10SCH40	0.077	0.038	150	5.7	5.7	22.6
Diagonal Beam	4	PIPE	PIPE24x1/2	0.256	0.126	106.1	13.3	53.3	213.2
Cross Beam	1	PIPE	PIPE18x1/2	0.191	0.094	75.0	7.0	7.0	28.1
								66.0	**263.9**
								Total (st)	**131.9**

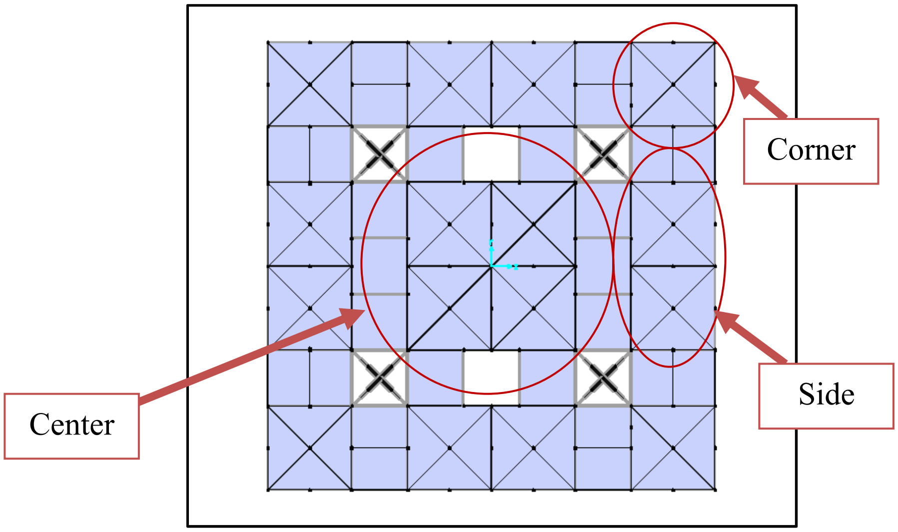

Figure 14: Top View of ClubStead SAP2000 model at Deck Level

4.4. Towers

The 100ft high towers are designed to sustain the compression loads due to the combination of vertical forces from the cables, of its self weight and of the vertical component of the wave loads on the columns.

API guidelines don't apply to the design of the towers because their thickness to diameter ratio is too slender. In this analysis, the tower is modeled as a cylindrical unstiffened pipe. Its diameter and thickness are assigned to obtain a factor of safety of about 10 on the buckling and yield strength ratio on the beam. The buckling ratio is the ratio of Euler maximum buckling strength to design compression force. It is defined as:

$R_B = \frac{P_E}{P_D} = \frac{\pi^2 EI}{kL^2 P_D}$ where E is the Young Modulus, I the inertia and L the length of the tower.

This is a preliminary calculation to assess the amount of steel needed to build the tower. It does not reflect the effect of the building structure on the tower stiffness.

The yield ratio is defined as:

$R_Y = \frac{MYS}{P_D / A}$ with MYS the maximum yield strength (50ksi) and A the cross section of the tower.

The maximum axial force on the towers, computed in the finite element analysis, is 2700 kips. This is the design load on the tower. A tubular tower of 22ft diameter and 0.625 in thickness provides sufficient cross section and inertia to obtain a factor of safety of 9.6:

Table 9: Strength of Tower

	Design Strength (kips)	Design Ratio
Euler Buckling	619,087	229.3
Axial Stress	25,918	9.6

The following table summarizes the equivalent amount of steel needed for the tower sizing.

Table 10: Summary of Weight of Towers

	cross section (ft2)	Weight (st)
1 tower	3.60	88.19
Total		352.77

The shape of the tower cross section may change to accommodate the design of the buildings. Since it will be inside the buildings, it will likely not be made of a watertight pipe but of a number of vertical beams. Due to these construction uncertainties, the effect of bending moment is not included in this analysis and a larger factor of safety is used instead in the design. Further analysis will likely allow for a reduction in weight since the safety factor approach is conservative.

5. Brief Overview of the Column Design

The columns are designed to withstand the following loads:

- Hydrodynamic and hydrostatic loads on the submerged part of the column
- Compression loads transferred by the cable tension – and, if necessary, bending loads
- Loads at the connection with the truss of the deck

They should also survive damage that may occur in collisions and from corrosion.

To ensure the strength of the columns, the layout of stiffeners and hull thickness are similar to those of an offshore structure with a 75ft draft. The submerged part of the column has standard stiffeners for cylindrical columns. Figure 14 shows the ring stiffeners that prevent local buckling and the longitudinal T-shape stringers (vertical stiffeners).

At the deck level, the column is connected to the truss and to the upper deck tower. The loads from the cables and trusses are transferred to the lower column through the tower beams that are spread along the circumference of the column.

To preserve stability in the event of hull damage in case of collision, the columns are compartmented. The compartments are delimited with stiffened bulkheads and watertight flats which add some structural weight.

Overall, the column is assumed to weigh **8lb/ft^3** of displacement.

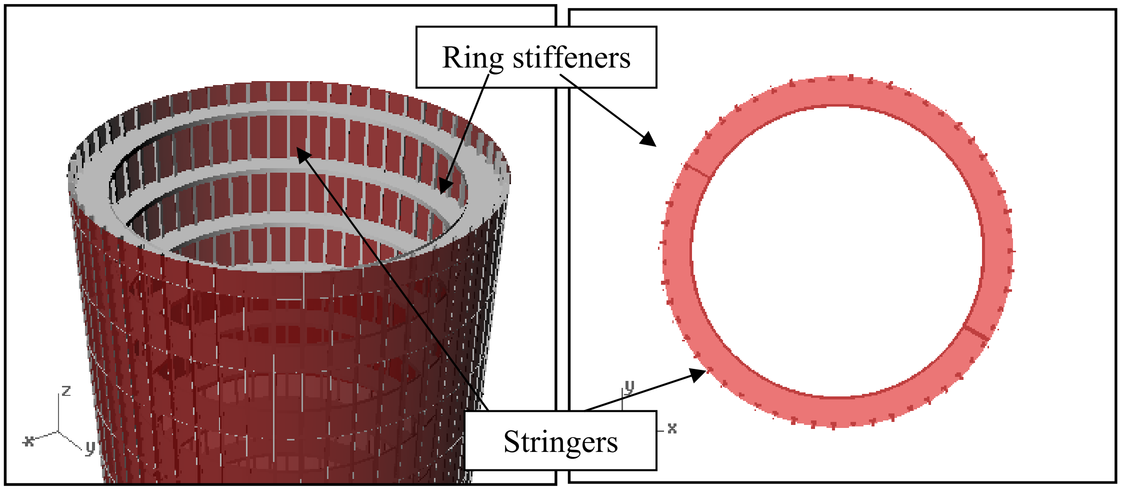

Figure 15: View of the inside of the submerged column (left: perspective; right: top)

Additionally, to preserve the integrity of the columns under corrosion, sacrificial anodes cover the submerged part of the external hull of columns. For enhanced protection in the wave area, the columns are covered with corrosion-protective painting (yellow part in Figure below). Also, in the water ballast internal tanks at the bottom of the columns, similar combinations of paint and anodes may be used to prevent internal corrosion.

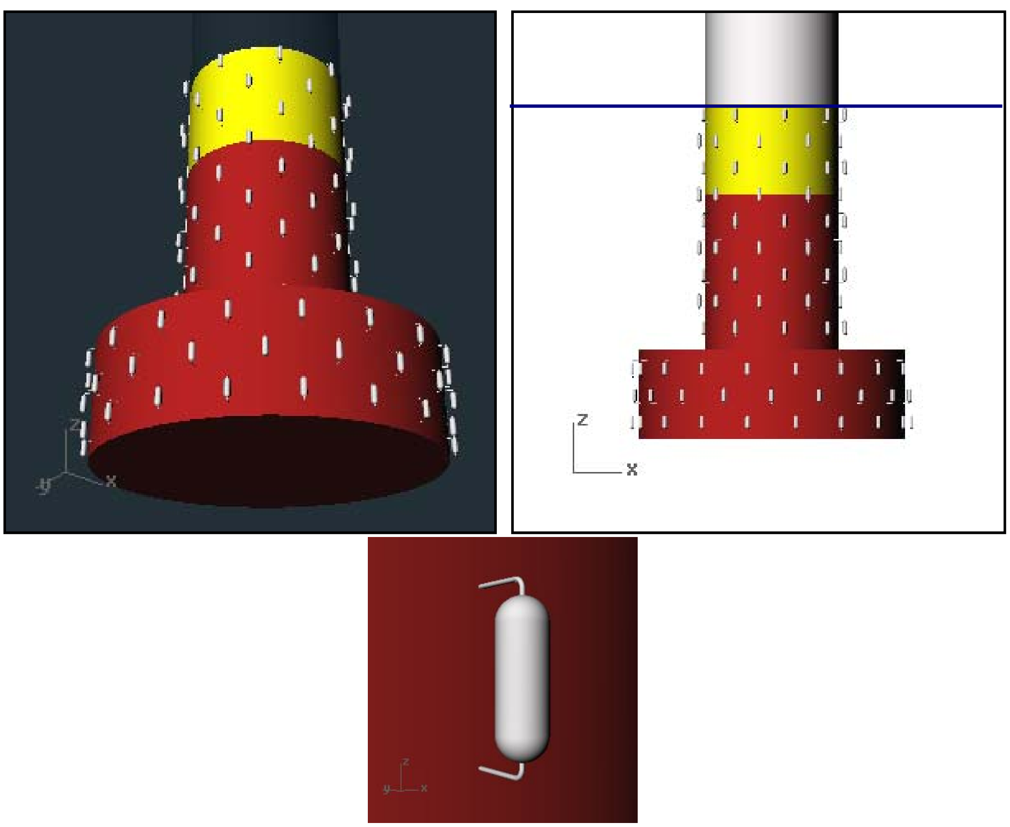

Figure 16: Cathodic protection on columns

References

[1] API Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design (RP 2A-WSD), American petroleum Institute, 21st edition, December 2000

[2] SAP 2000 Basic Reference Manual, Version 11, Computers and Structures Inc, 2006

[3] "*Rules for Building and Classing Mobile Offshore Drilling Units (2006)*", American Bureau of Shipping (ABS)