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FEASIBILITY AND DESIGN OF THE CLUBSTEAD: A CABLE-STAYED FLOATING STRUCTURE FOR OFFSHORE DWELLINGS

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ABSTRACT

The ClubStead is a novel type of offshore floating platform, which provides comfortable and safe ocean-going dwellings for communities of a few hundred people. The prospect of large, unclaimed ocean spaces has encouraged people to consider developing sea-going settlements. A number of attempts have been made on former oil platforms or cruise ships. But these structures are not designed for permanent living at sea and fall short of meeting dwellers' expectations. Efforts to build large, spacious floating living facilities have struggled to balance cost-effectiveness and structural integrity.

This paper describes an innovative, cost-efficient solution to maximize space on offshore structures. To control the cost, the submerged volume of the floater is minimized. To maximize comfort, the available living surface area is also maximized, while the motions of the platform are limited. The proposed solution is based on the principles of tensegrity, which are commonly used on bridges. Cable stays are tensioned at the top of towers to support the weight of both light and cantilevered top-sides. The floater is column-stabilized with four submerged columns.

A feasibility study was performed for the design of a Clubstead based off the coast of California. The platform is dynamically positioned and can house up to 270 people. Due to its primary function, as a floating living facility, the architectural design and the engineering studies are intertwined. Iterations are necessary to determine the global characteristics of the ClubStead. The buildings and living spaces are arranged by an architect, within specific offshore-related constraints. The resulting payload is calculated and thus used in the design basis to perform the engineering analysis. The feasibility study focuses on survivability and passenger comfort to assess the novel design. The survivability analysis is based on structural strength and motion predictions in a 100-year storm. Passenger comfort is evaluated in operational conditions.

KEYWORDS
Offshore Living Facility, Tensegrity, Column-stabilized, Architecture, Passenger Comfort.

INTRODUCTION

The design of floating structures is shaped by their function in the ocean space. The ocean has been exploited mostly to meet economic necessities. Ships are designed as means of transportation. Moored and bottom-fixed offshore platforms have emerged as the foundations for energy exploitation offshore. Meanwhile, the need for viable solutions to establish residence at sea is growing due to renewed interest in experimenting with nation and community building and in exploring new frontiers. But to this day, few communities have successfully settled permanently offshore. The principality of Sealand established on a former World War II British sea fort is the most notable example. Most other designs were derived from cruise ships. But ships are not best suited for permanent offshore settlements due to relatively large roll responses in beam waves. Large semi-submersible platforms, used in the oil and gas industry, are more stable but costly. Alternatively, Watanabe et al. (2004) highlight the developments of pontoon type structures in their review of Very Large Floating Structures. Considerable attention has been given to the design and construction of the MegaFloat in Japan, described by Kikutake (1998) and Kobayashi et al. (1998). But these large structures have small air-gap. They operate in shielded basins or need the protection of breakwaters. The present work introduces a new type of floating structure intended for long-term offshore dwellings in the open ocean. It is designed to provide a comfortable and aesthetically pleasing environment and to be able to handle open ocean weather. The ClubStead is a column-stabilized platform which relies on tensegrity to maximize its usable deck space.

A preliminary design of a ClubStead platform is laid out to illustrate the particular challenges of building offshore dwellings. Due to the importance of living spaces aboard and of integrating business and residential functions together, an architectural plan must be drawn early in the design. It must take into account the engineering constraints of offshore reliability. Conversely, the engineering analysis incorporates the preliminary architectural plan in its design basis. A methodology is developed to ensure the convergence of both the architectural and the engineering design. The viability of the concept is demonstrated herein with the design and analysis of a ClubStead for 270 people. The platform is assumed dynamically positioned 100 miles off the coast of San Diego, California. The dynamically-positioning system provides more flexibility to avoid potentially harmful storms, while removing potential permitting issues due to mooring interactions on the seabed.

A NOVEL DESIGN: FLOATING TENSEGRITY FOR OFFSHORE DWELLINGS

Before the initial concept was developed, the basic needs of the residents were identified. They fall into four categories:

– Autonomy of the Clubstead: the platform should be economically sustainable. Hence, the structure is designed to house business spaces. Business functions are embedded in the organization of the structure. A few alternatives are considered in the first phases of design. In one instance, the platform is arranged to include touristic facilities, with a casino and an offshore resort. In another example, the community could be focused on providing medical services.
– Passenger comfort. This is an essential feature of the platform. Life at sea can be harsh due to special restrictions and constant motions. The ClubStead needs to be spacious enough to provide sufficient living areas for its dwellers. The probability of sea-sickness must also be minimized to optimize passenger comfort.
– Passenger safety is critical for an ocean going vessel with passengers. To ensure the reliability of the structure in harsh ocean weather, the ClubStead is designed to survive a 100 year sea-state on site. Additionally, fire fighting and medical equipment and emergency evacuation plans are included into the building plans.
– Cost optimization of the project is a major condition to its feasibility. In the preliminary phase, it consists in minimizing the displacement of the platform. It can also be enhanced by planning for all phases of construction and installation.

A large floating structure must develop sufficient hydro-elastic strength to support the loading of large low-frequency water waves. Attempts with pontoon-type structures like the Mega-Float are limited to coastal areas and remain difficult to scale to open ocean operations. An alternative approach consists in raising the deck high enough above the waterline to protect it from direct wave interaction. This solution is applied on column stabilized platforms in the oil and gas industry. But the span between columns cannot be expanded in a cost effective manner and decks are typically shorter than 100 m.
The concept of the ClubStead draws on technological developments in bridge engineering during the 20^{th} century. As span length increased, the cost efficiency of cantilevered bridges diminished and they were slowly replaced by lighter alternatives involving cable support. Cable stayed bridges benefited from improvements in cable connection and material in the second part of the 20^{th} century and are now spread worldwide. Increasing the length of the deck on a floating structure may be compared to the lengthening of the span on cantilevered bridges.

On the ClubStead, semisubmersible technology is employed for adequate sea-keeping characteristics. To minimize the displacement while preserving sufficient stability, a column stabilized design is chosen. A footing at the base of the column lowers the center of gravity and increases the natural heave period for maximum stability of the platform in waves.

An extension of the deck beyond the column-enclosed space is achieved. The innovation resides in the addition of cable-stayed deck structures which do not need to be supported at both ends by a floating component. Support for the extended deck is provided by stay cables. The cables transfer the dead loads as compression to the top of the towers, above the columns. The use of such technology at sea is made possible by developments in anti corrosion systems for high-stress steel cables and the rise of carbon fiber cables as described by Meier (1992).

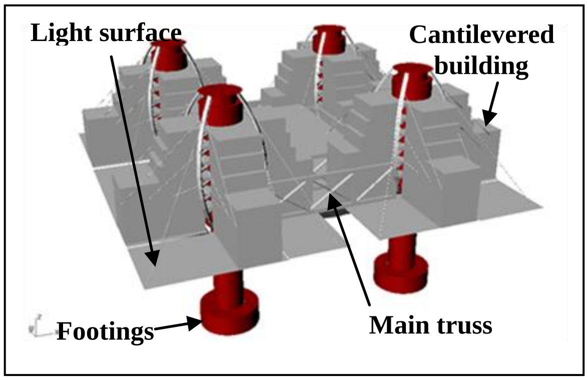

Figure 1: Representation of the ClubStead concept - columns and footings in red, deck structure in grey

The deck structure is a combination of three structural components as illustrated in Figure 1:

- Between columns, a large truss provides sufficient lateral stiffness to the platform and is also used to support heavy buildings
- On the extended deck, buildings may be supported. For these heavy deck structures, a light cantilevered truss is seconded by cable stays,
- Light deck surface areas on the extended deck and at the center of the platform are intended for recreational use. They are cable stayed.

Additional cables can be used below deck to counter the dynamic effects of wave induced motions on the suspended structures. The use of a horizontal cable between columns was also considered to enhance lateral stiffness.

AN ITERATIVE DESIGN APPROACH

The ClubStead is designed according to the offshore industry standards for passenger vessels and semi-submersible vessels. The following design codes are used for the hull and safety design:

- American Bureau of Shipping (ABS) Rules for Building and Classing Mobile Offshore Drilling Units, 2006

- American Petroleum Institute (API):

• API RP 2SK, Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures, 2005

• API RP 2A-WSD Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design, 22nd ed

- International Maritime Organization (IMO) International Convention for the Safety of Life at Sea (SOLAS), 1974

The design of the ClubStead is carried out iteratively. The design process is illustrated in Figure 2. After formulation of the conceptual idea, a design basis is written for a specific project. It provides the function, occupancy and location of the platform. The metocean conditions can be derived from archived environmental data measured at NOAA buoy 46047 which is located close to the chosen San Diego site.

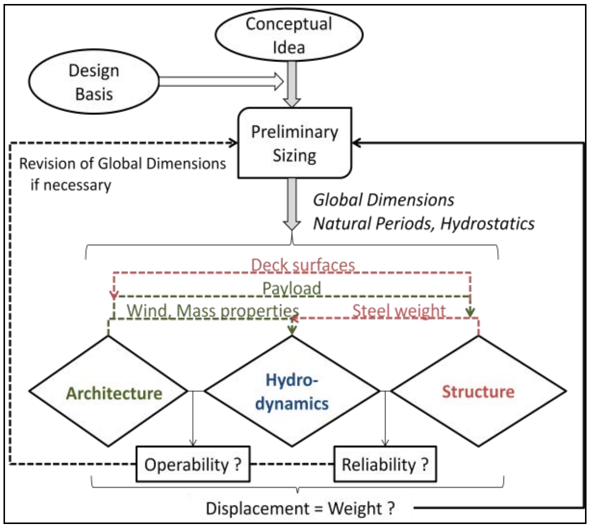

Figure 2: Iterative Design Process of ClubStead

A preliminary sizing is performed to meet basic requirements in hydrostatics and hydrodynamics. This phase determines the global dimensions of the platform, such as the column span and overall deck dimensions. These values are carried on to the next stage, which iterates between the architectural design and the structural sizing of the deck to determine the best use of deck space. The structural designer provides the architect with the deck space distribution by defining the areas available for buildings and those reserved for light spaces. The architect in turn lays out the buildings and provides the structural engineer with the dead loads on the deck. Both structural and architectural designs are translated into global mass properties and wind properties to perform the hydrodynamic analysis

The hydrodynamic analysis focuses on the rigid body response of the platform. It ensures that the motions are within acceptable limits in the given metocean conditions. To compute the time domain response of the ClubStead, hydrodynamic program TimeFloat is used. It is a 6-degree-of-freedom fully coupled hydrodynamic program which was developed to analyze the motions of floaters subject to environmental loads, non linear viscous loads due to shedding, mooring forces and any other mechanical forces. The program was described by Cermelli et al. (2004) and (2008). It uses diffraction-radiation software WAMIT as a pre-processor to obtain hydrodynamic coefficients and first order forces. These forces are converted in the time-domain by use of a Jonswap wave spectrum. Viscous and current forces are included in the equations with a Morison formulation. Wind forces are based on wind coefficients combined with an API wave spectrum. The wind coefficients on the ClubStead are generated for any directions based on a drag coefficient of 1. The DP system is modeled with a linear force using soft horizontal springs which are set up at the potential location of the thrusters, 10ft under the waterline to control the motions in surge, sway and yaw. The location of the thrusters should be confirmed in further design stages.

At the end of the hydrodynamic analysis, additional iterations of the structural and architectural design may be necessary to adjust the center of gravity or the wind area.

Eventually, the design process converges toward a solution and the fulfillment of basic requirements is verified. The operability of the design is judged by the degree of autonomy and the level of comfort aboard the platform. Its reliability is estimated based on the survivability criteria. If the global dimensions are such that the design is not satisfying at this stage, they should be revised and the process should be reiterated. When a solution appears, the consistence of the initial global dimensions with the mass properties is checked and additional iterations are run if necessary. The present paper does not describe the details of design iterations on the ClubStead. It focuses instead on the assessment of operatibility and survivability of the final design.

GLOBAL SIZING

The global dimensions of the ClubStead at the end of the iterative design process are summarized in Table 1. The dimensions on the deck are illustrated in Figure 3.

Table 1: Global Dimensions of ClubStead (in ft)

COLUMNS	
Column diameter	41
Footing Diameter	76
Footing Height	20
Draft	75
Air-gap	40
DECK	
Span between columns	200
Length of horizontal extension beyond column	100
Width of a building	50

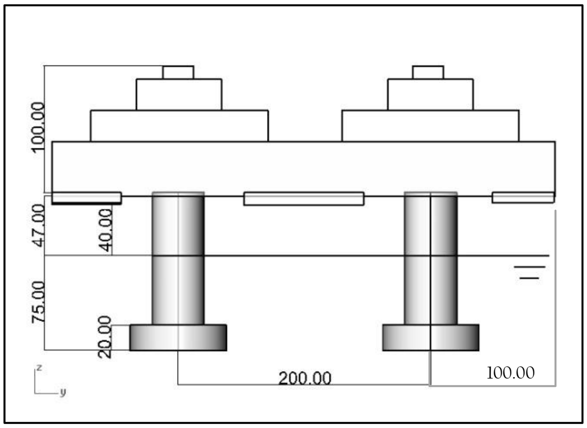

Figure 3: Dimensions of ClubStead (in ft)

The payload represents more than 30% of the displacement, in Table 2. This high ratio is made possible by the overall stability of the platform.
In the final architectural layout, a total of 368,200 ft^2 is available for passenger use on the ClubStead, including 90,000 ft^2 of open recreational surfaces. It does not include the machinery and maintenance areas. Based on an estimated 50 lb/ft^2 for buildings and 30 lb/ft^2 for open areas, the total payload is 7,705 st.
An estimated 2619 st of primary deck steel is necessary to support this payload.
The wind projected surface area is 41,680 ft^2 and the center of pressure is located 79.6ft above the mean waterline.

In operations, the metacentric height (GM) is 13.8ft. The heave natural period of the ClubStead is 17 seconds.

Table 2: Weight summary of the ClubStead (in short ton)

Structure:	
Hull steel	4386
Primary Deck steel	2619
Appurtenances	10
Total structure	**7016**
Payload:	
Machinery	414
Living Areas + Open areas	7705
Total	**8118**
Live loads (residents, diesel):	
Total	**575**
Ballast:	
Total	**5200**
Total weight:	**20908**

Mass properties for the hydrodynamic analysis are summarized in Table 3.

Table 3: Global mass properties of ClubStead after iterations on the structural and architectural design

Description		unit
Total Weight	20,908	st
Center of gravity above the mean waterline	19.5	ft
Radius of Gyration Rx	87.5	ft
Radius of Gyration Ry	87.5	ft
Radius of Gyration Rz	112.4	ft

PASSENGER COMFORT IN OPERATIONS

The comfort level aboard the ClubStead must be maximized during operational conditions. Passenger comfort is attained through architectural features and motion control. The architectural layout of the living spaces on the deck must be attractive and spacious. The following section describes how the architectural program of the ClubStead accommodates the necessities of an offshore design in a spacious environment. Additionally, passenger discomfort due to wave-induced motions of the platform should be minimized. This is verified by calculating the response of the platform in operational sea states.

Architecture

The initial program for the platform was an offshore resort with a luxury hotel and club casino intended to accommodate up to 270 people at a time. Although this first conceptual design was charged with spaces rendered for the hospitality program, the design of the platform and the conceptual form of the architecture can be used for a variety of business and residential functions. The flexibility is inherent to the form of the architecture.

The use of the available surface area of the platform must be optimized and the architecture must provide a sense of openness and space comparable to that of an onshore resort. It should feel more spacious than a typical cruise ship.

The architectural program takes into account a number of constraints. The layout of the architecture is driven by engineering considerations: the allocated area of the platform is limited to a 400'-0" x 400'-0" square deck surface; the maximum structural support for the architecture is provided on a 40ft wide strip between columns located 200'-0" apart from each other in plan.

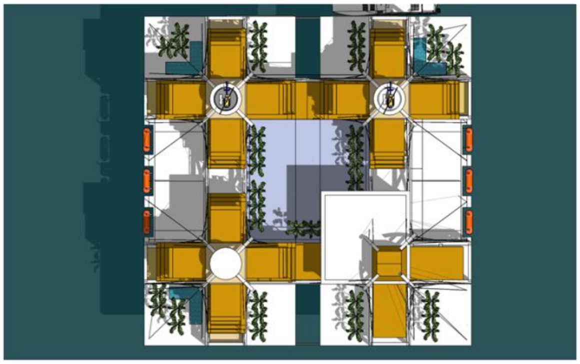

Figure 4: Top View of ClubStead Architectural Plan

The buildings are organized around the four main structural columns. The cruciform plan of the architecture at each column is supported by the primary 40'-0" box trusses described in the structural analysis. A pyramidal form at each column was adopted to provide maximum spatial openness. It also keeps the center of gravity low, by minimizing the weight at the upper levels of the buildings. A low center of gravity is critical to the stability of the platform.

Three of the four columns are dedicated to the program of the hotel for hotel rooms, staff quarters, function spaces, restaurants and bars and spa and fitness areas. The fourth column is a mechanical tower that houses the equipment and spaces needed for operations of the building and for life at sea. A club casino, or a large community space, is located near the mechanical tower and separated by sound and safety isolation walls.

Figure 5: General Perspective View of ClubStead Architectural Design

The hotel buildings have seven floors of interior spaces. The first floor houses a hotel lobby and back of house service spaces, retail spaces, restaurants, the spa and fitness amenities and public circulation. The second floor houses the staff quarters, function and meeting spaces along with additional spa and fitness level spaces. There are four levels of rooms above level two. The use of space is optimized by integrating rooftops into functional areas. The seventh level, or rooftop level, houses restaurant terraces and rooftop lounges. Vertical circulation of elevator and stairs for each tower are located inside the columns. There are also enclosed walkways at levels 2, 3 and 4 to provide cross-tower access.

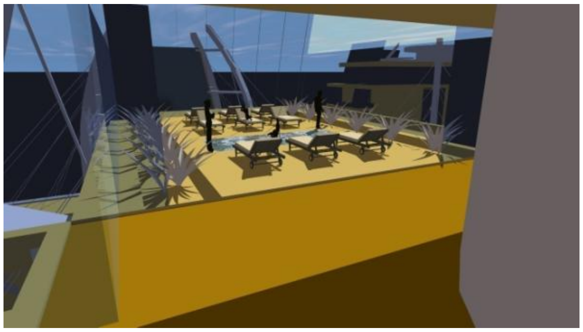

Figure 6: View onto a rooftop lounge on ClubStead

At the deck level, light-weight surface areas at the platform perimeter and center are suspended off the columns with cable stays; they provide recreational space for gardens, tennis courts, exterior dining areas, lookout points, etc.

Safety and maintenance spaces are reserved to meet the requirements of life at sea. A column is assigned to machinery. For the community to be autonomous, fresh water may be made aboard from sea water. A recycling center and a water and sewage treatment center provide maximum autonomy over waste management. A combination of diesel engines and solar panels will ensure the energy supply for utility and propulsion of the dynamically-positioned system. Additionally, the platform is equipped with safety equipments according to recommendations from the International Convention for the Safety of Life at Sea (SOLAS) organized by the IMO (International Maritime organization) in 1974 [1]. The architectural program makes room for a control room and safety center, a fire-fighting room and multiple fire stations, and a medical center. For easy access and evacuation, a boat landing and two helipads are included in the plan. Sufficient life-saving equipment is provided in accessible areas.

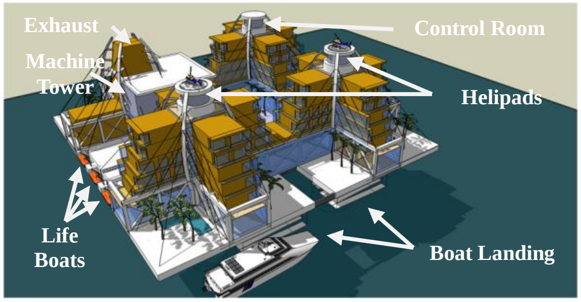

Figure 7: Control, maintenance and safety amenities aboard the ClubStead

The form of the architecture at the end bays of the hotel towers are shaped with sail-like transparent surfaces that echo the shape of the arch beams supporting the stay-cables. These surfaces provide large window bays for the penthouse room and maximize the views of the sea.

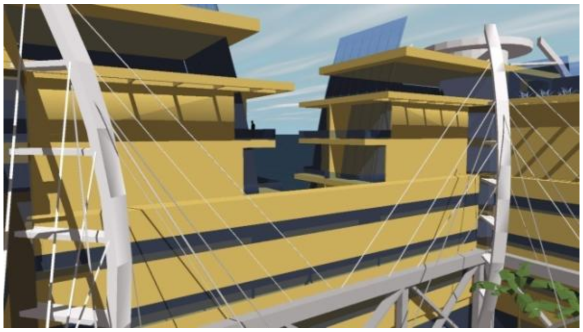

Figure 8: View of the cable stays and structural components outside the buildings

Engineering features such as the cable stays and trusses are integrated to the landscape. In this aspect, the ClubStead draws on works by architects such as Santiago Calatrava. Bent arcs are attached to the tower and support the cable. This configuration was chosen not only for its aesthetic advantage but also out of practicality, to avoid intersections between the buildings and cables.

Relative Motions in Operations

Research by O'Hanlon and McCauley (1974) has shown that the fraction of people who become sick onboard a vessel is a function of acceleration, excitation frequency and duration of exposure. The International Standard ISO 2631 states that, at typical wave peak frequencies, a majority of the passengers is seasick after being exposed to a vertical acceleration RMS of $0.25 m/s^2$ for 8 consecutive hours.

The 8-hour exposure curve is used to assess the level of comfort aboard the ClubStead. The RMS of heave, roll and pitch induced vertical acceleration is computed over 1-hour TimeFloat simulations for all sea-states in the wave scatter diagram. The environmental conditions are derived from 10 years of NOAA data. The waves at 0 degree heading are combined with the most probable 1-hour mean wind velocity at the given significant wave height. The vertical acceleration is computed at the locations represented in Figure 9.

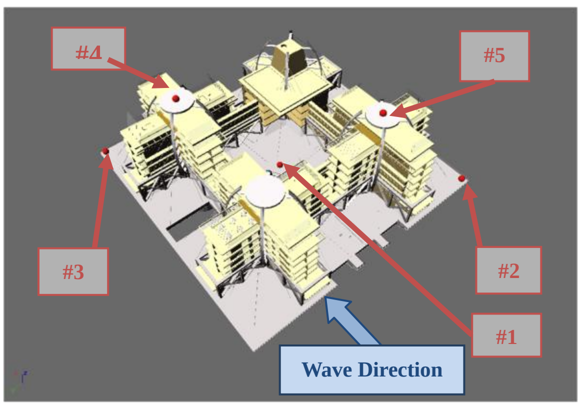

Figure 9: Locations to Compute Vertical Acceleration

Probabilities of exceedence are calculated based on the probability of occurrence of the sea-state:

$$P(RMS > a) = \sum_{seastate\, i} p_i \delta_{RMS_i > a} \quad (1)$$

where p_i is the probability of occurrence of sea-state i and $\delta_{RMS>a}$ is equal to 1 when the RMS of acceleration at the given sea-state is greater than a and 0 otherwise. Results are provided at chosen locations for $a=0.1\ m/s^{-2}$ and $a=0.25 m/s^{-2}$ in Table 4. The distribution of acceleration RMS is plotted in Figure 10.

Table 4: Probability of Exceedence of Vertical Acceleration RMS

	Probability of Occurrence (%) of Vertical Acceleration RMS > than	
Position	0.1 m/s2	**0.25m/s2**
Center of deck	43	1.3
Extremity of Deck 2	65	1.5
Extremity of Deck 3	72	5.4
Top of Tower 4	48	1.3

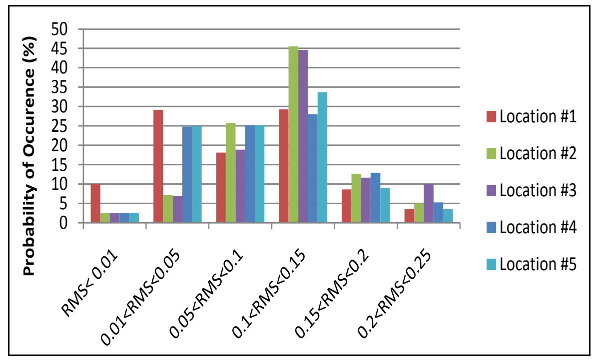

Figure 10: Probability of occurrence of level of vertical acceleration aboard the ClubStead

The NORDFORSK project (1987) published criteria per type of vessel and activities. It states a line cruiser should offer maximum comfort among ships with an acceleration RMS below 0.02*g* ($0.2 m/^{s-2}$). This level of comfort is attained between 90 and 97% of the time on the ClubStead.

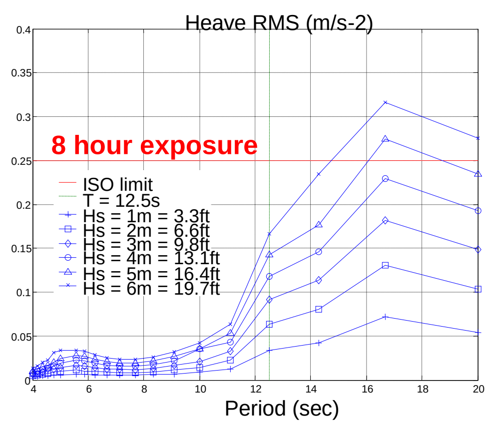

Figure 11: RMS of vertical acceleration - center of deck (position 1)

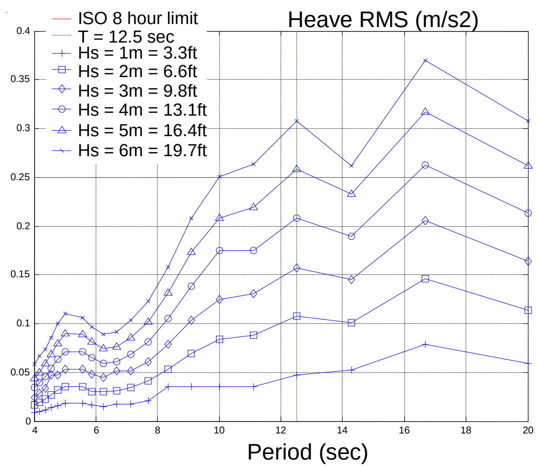

Figure 12: RMS of vertical acceleration - extremity of deck (position 3)

Long period waves, with peak periods larger than 10 seconds, are frequent at the San Diego site. Passenger comfort could be further improved by increasing the heave natural period. It is illustrated in Figure 11 and Figure 12 which represent the vertical acceleration RMS as a function of peak period Tp for significant wave heights Hs between 1 and 6m. Discomfort increases with Hs but the wave period has the most significant effect. The discomfort level peaks at the heave period of resonance of the platform, around 17 seconds. Notably, the discomfort level increases also on the extremities of the platform for Tp=12.5sec. This is consistent with the increase in pitch and roll RAO at this period.

RELIABILITY IN SURVIVAL CONDITIONS

According to API recommendations, the ClubStead is designed to survive the loadings and motions in a 1-year, 10-year and 100-year return storm at the intended site. A Weibull fit on the historical data provides the most probable extreme sea-states described in Table 5.

Table 5: Extreme Sea States off San Diego, CA

Return Period		1 year	10 year	100 year
Hs	*m*	7.0	7.7	8.3
Tp	*s*	14.3	14.3	14.3
Wind Speed	*m/s*	16.0	17.5	18.9
Current Speed	*m/s*	0.48	0.53	0.57

The survivability criteria of the ClubStead are defined as follows:

- The structural integrity of the platform is not affected by extreme wave and wind loadings.
- Green water remains clear of the deck, with a minimum clearance of 5ft.
- Maximum pitch and roll angle do not exceed 10 degrees.

These conditions are based on typically recommended practice for offshore structures. Structural and hydrodynamic analyses are carried out to ensure that the dimensions and characteristics of the ClubStead are sufficient to fulfill the criteria.

Structural integrity

The preliminary structural analysis aims at estimating the amount of steel to build the ClubStead. This is necessary to obtain the mass properties for the hydrodynamic analysis. It is also used to derive a preliminary cost estimate of the platform.

The main structural components of the ClubStead are:

- The four columns and footings, which will be compartmented and stiffened according to offshore industry standards, such as the ABS MODU rules. These are common elements on semi-submersible hulls. In this preliminary analysis, the steel density is assumed equal to 8lb/ft^3, which was determined sufficient for a semi-submersible of similar draft by Aubault et al (2009).
- The deck primary structure consists of the main truss which supports the wave loads and the dead loads of the buildings between columns; the secondary truss which supports the cantilevered areas with buildings; and the simple beams to help maintain the cable stayed light-weight surfaces. The sizing of these beams and trusses is carried out using a finite element analysis. It is described herein.
- The towers and cable supporting arcs, on top of the columns, are designed to withstand the compression and bending moment from the cable tension. These internal forces are computed with the same finite element model.

The truss and beams consist of tubular members. The design of the deck primary structure is based on API Recommended Practice 2A - Working Stress Design. The feasibility study focuses on the strength analysis to provide an estimate of primary steel weight. A fatigue analysis on the truss connections should be performed in further stages. The overall structural integrity of a member is assessed by computing combined axial and bending stress ratios. All computed ratios must be less than 1.0 to comply with API RP2A-WSD.

A finite-element model is built in finite element program SAP2000 version 12. The primary structure of the ClubStead is analyzed within the framework of beam theory. A static analysis is run to determine the internal forces in the deck primary structure, starting with small tubular sizes on the trusses and beams. Cables are included as tendon elements with a given pretension to model the effect of stay cables on suspended surfaces. The detailed analysis of the cable 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.

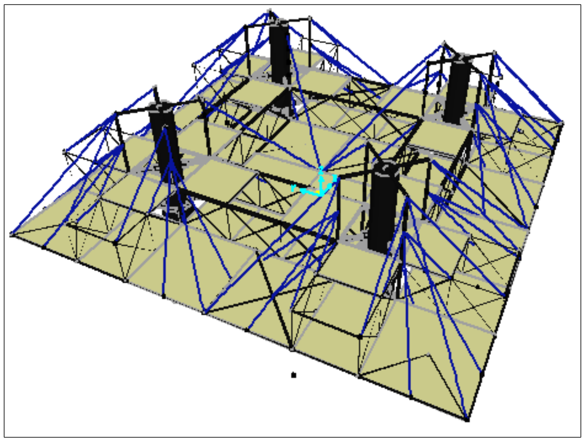

Figure 13: Finite Element model of the ClubStead in SAP 2000 v12

Applied loads on the platform include:

- Dead loads:

The weight of the buildings on the primary deck structure is applied by assigning distributed loads on 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 a Morison formulation, based on a linear Airy wave potential. The most extreme wave loads are associated with the squeezing and prying modes at 0 and 45 degree heading waves, as illustrated in Figure 14. The characteristics of the design waves are summarized in Table 6. Wave heights were chosen to provide conservative results. The wave periods are calculated based on deep water theory. Buoyant forces are also included.

Table 6: Characteristics of Airy Waves used to size the ClubStead primary structure

Wave #	Wave length (ft)	Wave Direction (deg)	Wave Period (sec)	Wave Height (ft)
1	565.7	45.0	10.5	40
2	282.8	45.0	7.4	35
3	400.0	0.0	8.8	35

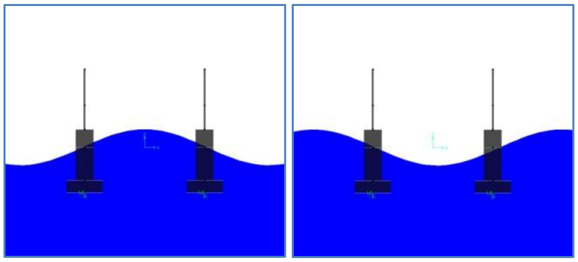

Figure 14: Squeezing and Prying modes of extreme wave loads

- Wind loads, propulsion loads and secondary forces are neglected in this preliminary analysis. Wind vibration on the deck should be the object of a detailed analysis.

The static analysis is iterated until an appropriate design is found. At first, only the main trusses are included to ensure they are designed to support the wave loads alone. Main trusses are 40ftx40ftx150ft truss boxes. They have three bays with large horizontal pipes to resist the wave loads. Diagonal beams provide additional support. Eventually the cantilevered trusses and light-weight areas are added with their supporting cables. Several iterations are necessary to determine the most appropriate configuration of the trusses and cable layout. The final finite element model is represented in Figure 13.

Other configurations were considered to provide lateral support to the main truss. For instance, a small pontoon or bracing between the keels would reduce lateral loads at the deck level.

Extreme Motions in Storms

The rigid body motions of the platform are computed for 3-hour simulations of the 1 year, 10-year and 100-year storms, with time-domain hydrodynamic program TimeFloat.

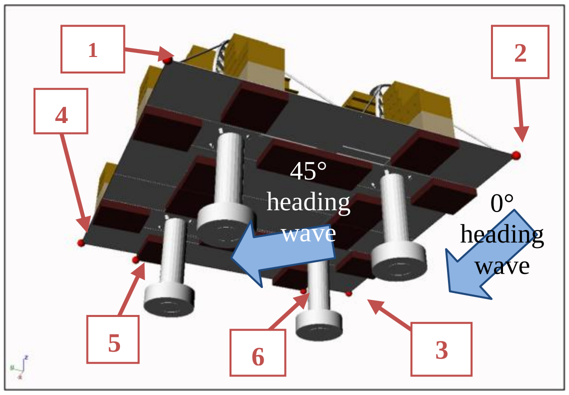

Figure 15: Wave gage position on ClubStead to compute green water level

To verify that the deck remains clear of the wave crest throughout extreme weather conditions, time series of relative positions of the deck and wave crest are calculated at several critical locations. The position of six such "wave gages" is represented in Figure 15 with a red dot.

The statistics of motions are computed over each three-hour simulation. Results are provided in Table 7 and Table 8 for the 100 year return storm in two wave directions.

Table 7: Statistics of motions (in ft and deg) and of wave gage position above crest (in ft) in a 0 degree heading 100 year return storm

100 year - 0 deg		Mean	RMS	Max	Min
Wave	height	0.11	6.79	27.34	-28.96
Motions	surge	48.36	5.73	76.18	32.36
	sway	0.42	0.05	0.69	0.30
	heave	-0.01	6.42	19.56	-19.86
	roll	-0.03	0.05	0.13	-0.20
	pitch	1.76	0.97	5.45	-3.10
	yaw	-0.56	0.10	-0.26	-0.98
Wave Gages	1	53.19	8.47	85.31	22.79
	2	52.97	8.44	85.56	23.07
	3	40.97	7.55	64.86	13.70
	4	40.75	7.57	65.30	12.65
	5	33.79	7.56	58.17	5.83
	6	33.93	7.55	57.90	6.49

Table 8: Statistics of motions (in ft and deg) and of wave gage position above crest (in ft) in a 45 degree heading 100 year return storm

100 year - 45 deg		Mean	RMS	Max	Min
Wave	height	0.16	6.79	27.21	-28.71
Motions	surge	37.24	3.98	58.56	25.87
	sway	35.83	3.94	56.13	24.47
	heave	0.00	6.40	19.38	-20.08
	roll	-1.18	0.68	2.30	-3.70
	pitch	1.30	0.67	3.90	-2.17
	yaw	2.40	0.12	3.20	1.92
Wave Gages	1	55.66	8.66	86.55	27.25
	2	47.28	8.96	79.40	16.54
	3	46.48	8.85	76.14	17.05
	4	38.40	8.15	66.84	9.35
	5	32.92	7.59	58.25	6.08
	6	37.96	8.50	66.17	10.87

The minimum clearance between the deck and the wave crest is 5.83ft. The maximum pitch and roll angle is 5.45 degrees.

This analysis proves the reliability of the ClubStead in extreme conditions. Empirical data is necessary to ascertain parameters used in the numerical model. Numerical modeling of 1st order wave motions is highly accurate, but drag coefficients and air-gap are best determined with model testing.

CONCLUSION

The conceptual idea of the Clubstead is founded on semisubmersible hull technology combined with cable stays to extend the deck surface area. This floating structure offers a maximized deck space on an ocean-going platform. The use of cable stays minimizes the payload, hence the displacement and results in a cost effective solution. Static and dynamic stabilities are provided by a column stabilized plan with large footings. A design was presented above for a tentative community of 270 people living in the Pacific Ocean off the coast of California. It illustrates the complex process entailed in the design of a cable-stayed floating platform for permanent offshore residences. The importance of involving an architect early in the design process is highlighted. Interactions between the architectural and engineering teams are essential. They ensure the living facilities are both comfortable and reliable. They also help identify cost saving opportunities associated with the relative position of structural components and architectural features. The structural skeleton of the deck on a floating city has the double function of supporting dead weight, like an onshore structure, and providing lateral stiffness to resist environmental loadings. This must be taken into account in the architectural layout. An iterative process ensures that the platform is optimized within its design basis. The ideal ClubStead provides maximized comfort and autonomy onboard for an acceptable level of safety in the most cost efficient manner.

Further work is needed to determine how to properly adapt stay cable technology to floating platforms. The effect of wind and wave dynamics on the cable loadings must be assessed. Connectors may need some additional damping systems. This will be best determined with further static and dynamic structural analysis of the system. An extensive fatigue analysis of the cables and truss connections should be performed in later stages. In the swell dominated environment of the Pacific coast, fatigue is likely to be a significant factor in the structural design. Additionally, corrosion control of the structure and cables should be planned for, using cathodic protection and non-corroding materials for instance. To validate the air-gap calculations in a 100 year storm, the platform should be tested experimentally. Model tests remain an important step to qualify offshore structures and validate numerical results.

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REFERENCES

[1]. Kikutake T., A Mega-Float Airport, the State of the Art, *Proceedings of the 17th Intl. Conference on Offshore Mechanics and Arctic Engineering*, OMAE 1998

[2]. Kobayashi K., Ohkawa Y., Futami Y., Large Scale On-Sea Experiment of Mega-Float Structures, *Proceedings of the 17th Intl. Conference on Offshore Mechanics and Arctic Engineering*, OMAE 1998

[3]. Watanabe, E., Utsunomiya, T. and Wang, C.M, "Hydroelastic analysis of pontoon type VLFS: A literature survey," *Engineering Structures*, **26**(2), 245-256, 2004

[4]. Walther, R., *Cable Stayed Bridges*, Thomas Telford Publishing, 1999

[5]. Meier, U., Carbon Fiber Reinforced Polymers: Modern Materials in Bridge Engineering, *Structural Engineering International*, Vol.2 No.1, 1992

[6]. Cermelli C.A., Roddier D.G., Aubault A., "WindFloat, a Floating Foundation for Offshore Wind Turbines: Hydrodynamic Analysis", *OMAE 2009*, Honolulu, HI, USA

[7]. Cermelli, C.A., Roddier D.G., and Busso, C.C., "MINIFLOAT: A Novel Concept of Minimal Floating Platform for Marginal Fields Development", *Proc. of 14th Intl. Offshore and Polar Engrg Conf (ISOPE)*, Toulon, France, 2004

[8]. Tzonis, A., *Santiago Calatrava: Complete Works*, New York, Rizolis, 2004

[9]. O'Hanlon, J.P. and McCauley, M.E., 1974, "Motion Sickness Incidence as a Function of the Frequency and Acceleration of Vertical Sinusoidal Motion", *Aerospace Medicine*, 45(4):366-369.

[10]. International Organization for Standardization, Specification 2631-1:1997, *Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements*

[11]. NORDFORSK 1987 The Nordic Coopera-tive Project for Seakeeping Performance of Ships, Assessment of a ship performance in a seaway, MARINTEK. (Cited within Faltinsen 1990).

[12]. Aubault A., Cermelli C.A., Roddier D.G., "WindFloat, a Floating Foundation for Offshore Wind Turbines: Structural Analysis", *OMAE 2009*, Honolulu, HI, USA