Liftboat
Elevated Structural Analysis

By W. P. Stewart[1]

Paper presented to SNAME
Texas Section Meeting,
August 16, 1990

The structural analysis of liftboat legs and liftboat main hull structures has been the subject of much recent interest as a consequence of new Coast Guard inspection requirements for this category of previously uninspected, self-elevating offshore service vessel. A brief history of the development of liftboats and a comparison of their design requirements with those of jack-up rigs is given.

The paper goes on to describe the analysis procedures developed by the author for the Coast Guard for the specific task of liftboat leg strength analysis. Of particular importance are the end fixity conditions of liftboat legs. At their upper ends, liftboat legs are restrained by horizontal guide reactions and vertical pinion reactions. At their lower ends, liftboat legs are welded to relatively large footings. These footings, or pads, are restrained by reactions with seabed soils. The overall leg condition has in the past been characterized by a K-factor, or effective length factor, which accounts for the support conditions at the ends of the legs. Using a K-factor alone is shown to be inadequate in the analysis of liftboats.

1 President, Stewart Technology Associates, Houston.

Liftboat Elevated Structural Analysis

W. P. Stewart[1]

Paper presented to SNAME Texas Section Meeting, August 16, 1990

The structural analysis of liftboat legs and liftboat main hull structures has been the subject of much recent interest as a consequence of new Coast Guard inspection requirements for this category of previously uninspected, self-elevating offshore service vessel. A brief history of the development of liftboats and a comparison of their design requirements with those of jack-up rigs is given.

The paper goes on to describe the analysis procedures developed by the author for the Coast Guard for the specific task of liftboat leg strength analysis. Of particular importance are the end fixity conditions of liftboat legs. At their upper ends, liftboat legs are restrained by horizontal guide reactions and vertical pinion reactions. At their lower ends, liftboat legs are welded to relatively large footings. These footings, or pads, are restrained by reactions with seabed soils. The overall leg condition has in the past been characterized by a K-factor, or effective length factor, which accounts for the support conditions at the ends of the legs. Using a K-factor alone is shown to be inadequate in the analysis of liftboats.

Introduction

Liftboats are self-propelled vessels, generally with barge-shaped hulls, and three or more independent legs. These legs are raised and lowered relative to the hull, driven by hydraulic motors and rack and pinion gear systems. The legs have large footings, or pads, on their lower ends, designed to support the legs on soft sea beds, with their hulls raised out of the water. The main function of these vessels is to provide a work platform for offshore construction and maintenance operations. They generally have one or more cranes and can carry deck cargo and offshore work crews, divers, and special equipment to a work site. Once at the site they elevate their hulls out of the water and serve as stable work platforms. Typical assignment durations at a given location vary from less than one day to several weeks.

There are presently 266 liftboats in existence (Reference 1) and the great majority operate in the coastal waters of the Gulf of Mexico. They first came into service in the 1970's (Reference 2) and were initially exempted from USCG construction and inspection standards, partly because they were under 300 gross tons, and partly because they were not thought (by the Coast Guard) to carry passengers or freight for hire. They were allowed to operate as "uninspected vessels" subject to the provisions of Sub-chapter C of Title 46 of the Code of Federal Regulations. These regulations are applied to other uninspected vessels such as recreational boats, towboats, and commercial fishing vessels, and (Reference 2) provide only basic, minimal requirements for lifesaving and safety equipment.

As the numbers of liftboats increased, they also began operating in deeper waters and venturing further from safe havens. Casualties increased and led the Coast Guard to conclude that they should apply "offshore service vessel" (OSV) regulations to liftboats. In 1987 there was a Notice of Proposed Rule Making (NPRM) to this effect, published in the Federal Register, and implemented by Change 1 to Navigation and Vessel Inspection Circular (NVIC) Number 8-81, issued in the spring of 1988. In the NVIC Change, liftboats are made subject to some OSV regulations and some self-elevating MODU (mobile offshore drilling unit) regulations.

---

1 President, Stewart Technology Associates, Houston, Texas.

Implementation of the inspection process is now under way for existing liftboats and the first vessels designed and built with Coast Guard approval are due to be delivered this summer (Reference 3). The inspection process is generally subject to The Liftboat Supplement to the Guide for Preparing Offshore Supply Vessels for Coast Guard Inspection, CDIG Memo No. 72, May 1, 1989. A Certificate of Inspection (COI) is granted if the vessel is found to be in compliance with the standards laid out in NVIC 8-81 Ch. 1. Up to 18 months is given to owners to clear up any deficiencies.

On May 9, 1989, another NPRM relating to liftboats was published in the Federal Register clarifying some inconsistencies in the previous NPRM and NVIC. At the time of writing (July 1990) these regulations had not become effective.

This paper addresses just one aspect of the certification process that is now being applied to liftboats, namely the elevated structural requirements. In the elevated condition, liftboats have very little similarity to "normal" OSV's and present special problems, not only of analysis, but also problems with the definition of what maximum environmental conditions are appropriate for design. Typical liftboat dimensions are shown in Figures 1-4.

Fundamental Design Criteria

As with a self-elevating MODU with independent legs (or jack-up) a liftboat should meet three fundamental design criteria (Reference 4) when elevated at any particular location:

a) ***It must have sufficient stability to withstand overturning. (Safety factor of 1.1 recommended, in accordance with ABS, Reference 12)***

b) ***No individual leg load (vertical soil reaction) as a consequence of operating weight distribution and forces acting on the vessel, should be allowed to exceed that load to which the leg was preloaded.***

c) ***No individual structural member load should be allowed to exceed that for which the member was designed.***

In fact criterion b) is normally relaxed to permit a larger vertical load than preload, provided that the additional leg penetration is tolerable. By "tolerable" it is meant that criteria a) and b) are still met satisfactorily. Additionally, as for a mat-supported jack-up rig (and for an independent leg rig, but this is rarely a limiting criterion) a fourth constraint should be met:

d) ***The lateral sliding resistance of each individual footing should be greater than the maximum predicted lateral load applied to each individual footing.***

Appropriate Environmental Conditions for Design

With jack-ups, the design maximum environmental conditions that any rig can survive are specified by the designer and, if approved by the Classification Society (eg ABS), become the maximum allowable conditions specified in the rig's Operations Manual. To be in compliance with Coast Guard requirements, the rig must be operated within the limitations of its Operations Manual, these limitations governing loading and environmental conditions in the afloat and in the elevated conditions.

When a liftboat is designed the designer has to decide what environmental conditions the vessel will be able to withstand. The vessel must be versatile and economically competitive. It must be able to work in as deep as water as possible, withstand as harsh an environment as possible when elevated, for as long as possible, in as soft a sea bed as possible, with as large a variable load as possible, which it must be able to elevate as quickly as possible, with the minimum of maintenance costs and the maximum of reliability. It should be able to transit as quickly as possible in as harsh an environment as possible, carrying as large a variable load and as many passengers as possible, for as little fuel and maintenance costs as possible. It should have shallow draft and narrow beam in order to get into as many potential harbor and dock facilities as possible. This list could be extended, but the point is made that the design is not for a particular location, or for a particular exposure duration.

Having noted the designer's dilemma, it must be noted that even for the more tightly regulated jack-ups, there is presently a lack of complete agreement as to what design environmental conditions any vessel should be able to safely withstand on a particular location, when the duration of the vessel's work at the location is known. The question is partly one of acceptable risk level for non-permanent structures.

In the North Sea it is becoming standard practice for some leading oil companies (and Certifying Authorities may follow suit) to require a full structural dynamic analysis for any jack-up for every new location it drills. This is partly because the particular combination of maximum environmental parameters at a given location is rarely coincident with any of the combinations specified in the Operations Manual. It is also partly due to new understanding of the response characteristics of jack-ups. Some oil companies are beginning to require similar analyses for jack-ups in the Gulf of Mexico, and one or two oil companies perform their own in-house analyses to ensure that potential jack-up rigs that they could hire for a given location have adequate structural performance characteristics.

Shell (SIPM) have written their own *Practice for the Site-Specific Assessment of Jack-Up Units* (Reference 5) which they apply in the north sea and in other areas of the world where SIPM operate. In this document they specify that a minimum return period, for environmental conditions, of 50 years be used (site specific) in order to assess the design adequacy of a jack-up for a given location, if it is to be manned. Although not explicitly stated, it is implied in the SIPM guidelines that the unit will be on location for several weeks as a minimum. If it is to be used only in the fair weather season, the assessment is to be based on seasonal conditions having a minimum return period of 50 years. SIPM practice is to use a ten-year return period for assessment of jack-ups that will be evacuated before extreme storm events strike, although it is not clear what environmental criteria they would apply to jack-ups in the hurricane season in the Gulf of Mexico.

It is interesting to note that the SIPM document requires rather extensive analysis procedures, using techniques that border upon the level of academic research and have certainly never been common practice in the jack-up industry. As justification for this their document cites the following reasons:

- ***lack of consistency within the jack-up industry on procedures and criteria for location assessment of lack-ups;***

- ***general increase in type of application (not only drilling but also accommodation units, early production platforms, construction support vessels, etc.);***

- ***moving into deeper waters and more harsh environmental conditions (in these areas the dynamic response can no longer be ignored);***

- ***historically separate development from fixed structures (little or no feedback of experience from the fixed structure industry).***

There are many similarities between the reasons offered by SIPM and the conditions faced by the Coast Guard with the liftboat industry. A comparison can be made between the liftboat industry and the jack-up industry, just as the jack-up industry is compared to the fixed structure industry by SIPM, in that there has been little or no feedback of experience from the jack-up industry into the liftboat industry. Instead, liftboats have been more closely aligned with work boats.

Most of the jack-ups used in the Gulf of Mexico have the capacity to withstand a winter storm loading (Reference 6) and generally the 10-year return period storm at typical operating depth in the hurricane season. Because these jack-ups are able to be readily de-manned, they are not generally capable of withstanding a 50-year storm return event in the hurricane season. Noble Denton in Houston (Reference 7) use a 10-year return period characterization of the environment in the hurricane season, for the purpose of jack-up location approval. Additionally they require a minimum air gap to accommodate a 50-year return period hurricane season wave height. In the non-hurricane season they use a 50-year return period characterization of the environment for jack-up location approval.

It must be noted that, unlike the North Sea, there are no generalized guidelines for wave heights or wind speeds appropriate for design for different return periods in the Gulf of Mexico. It must also be noted that there are rather diverse jack-up designs working in the Gulf of Mexico and some have significantly greater survivability than others. This is also true of fixed structures, some of which were designed over 25 years ago. For both fixed structures and jack-ups, design criteria have evolved with time, but in both cases, rather good safety records have been achieved.

The most commonly accepted environmental design criteria in the Gulf of Mexico are published by the API in Reference 8. From this document the 100-year return period wind speed to be used with simultaneous co-directional waves and currents is 98 mph (at 33 feet above sea level). This is a 1-hour wind speed. To convert this to a ten-year return period 1-hour wind speed, one can use the data in table 3.3.1 in Reference 9. For various locations on the coastline of Texas and Louisiana, the 10-year wind speed is approximately 0.75 times the 100-year (one-hour) wind speed. This data includes the combined influence of hurricanes and non-hurricane winds. Hence the 10-year wind speed from API data would be:

1-hour maximum speed = 0.75 * 98 = 73.5 mph

Reference 10 provides a means to convert the one-hour wind speeds in Reference 8 to 30-second wind speeds. The conversion factor is a multiplier of 1.22. Then to get from mph to knots, the multiplier is 0.868. Hence the API 30-second wind speed (used for jack-up response analysis) with 10-year return period, to be used with simultaneous waves and current is:

30-second, 10-year maximum speed = 73.5 * 1.22 * 0.868 = 78 knots.

For determination of the 1-year return period maximum 30-second wind speed the data in Reference 10 has to be extrapolated. The result is shown in the calculation below:

30-second, 1-year maximum speed = .44 * 98 * 1.22 * 0.868 = 46 knots.

Intuitively this value is low.

A 1-year return period wind speed is suggested to replace this extrapolated value of 60 knots.

The API (Reference 8) wave heights with 100-year return period are referenced to water depth. At 50 feet water depth, the 100-year return period maximum design wave height is in the range

43 to 48 feet. At 100 feet water depth, the design wave height is in the range 53 to 68 feet. In Reference 11 a variety of wave measurement programs and hindcast studies are compared. A relationship between deep water maximum wave heights and return periods, based on historical hindcast studies of Gulf of Mexico hurricanes is given, indicating that the height of the 10-year return period wave is 0.67 times the height of the 100-year return period wave. In a simplified approach, the same ratio may be considered to exist in shallow water.

Using API 100-year wave height data and the return period ratio from Reference 11, the 10-year and 1-year maximum wave heights of interest for liftboats are found as:

Max.10-yr.wave ht. in 50 feet water depth = 0.67 * 48 = 32 feet

Max.10-yr.wave ht. in 100 feet water depth = 0.67 * 68 = 46 feet

Max.1-yr.wave ht. in 50 feet water depth = 0.29 * 48 = 14 feet

Max.1-yr.wave ht. in 100 feet water depth = 0.29 * 68 = 20 feet

The above figures for wave heights must be combined with wave periods and currents. The deep water wave steepness values from Reference 8 are in the range 1/11 to 1/15. The 1/11 steepness gives equivalent deep water wave periods of 8.3 and 9.9 seconds for the 10-year return period waves, and 5.5 and 6.6 seconds for the 1-year return period waves. In shallow water the waves may become much steeper. Generally steeper waves will be more damaging to liftboats, but a range of wave periods should be investigated during design.

Currents are generally greater in shallow water as a consequence of tidal action. Reference 8 suggests a tidal current of 0.6 knots maximum, away from inlets. Wind generated currents may have up to 3% of the 1-hour wind speed in hurricanes and up to 1% of the 1-hour wind speed in winter storms according to Reference 8, which also notes that "as the storm approaches shallower water and the coastline, the storm surge and the current can increase". A reasonable interpretation of these guidelines is to take the following currents for liftboat design:

10-year return period current = 2.5 knots

1-year return period current = 1.7 knots

Restricted versus Unrestricted Classification

If liftboat design practice is to learn from the jack-up industry, the capability of vessels to operate in predefined storm conditions, as well as predefined water depths, will become standard practice. A significant difference is the duration of liftboat exposure to storm conditions compared with typical exposure durations for jack-ups. Few jack-ups are self-propelled and generally remain on location (evacuated) during hurricanes.

Frequently a liftboat will return to port at night. It is unusual for operations at the most remote offshore locations to last longer than a week or so. However, liftboats are gradually becoming larger and their range of operations is increasing. Hence the possibility for extended offshore service without the ability to return to port in a few hours must be considered. Therefore the Coast Guard is proposing a series of design criteria for liftboats. The "highest" rating would be for unrestricted service, with maximum design environmental conditions similar to those specified for OSVs for afloat stability, where waves have not traditionally been defined. For elevated stability the unrestricted service environmental criteria are less clear, since the structural response is strongly influenced by wave and current loading, as well as wind. A lower rating is for restricted service, and the definition of the environmental conditions for this rating is currently a matter of negotiation with owners and designers.

It is recommended that the minimum environmental conditions for which new liftboats are designed (for restricted service) corresponds to the 1-year return period conditions as defined above. It is noted that the derivation of these values by others may vary. However, they serve a basis for consistent design practice which is discussed in the next part of this paper. For unrestricted service, it is recommended that the minimum design criteria should be 10-year return period criteria if the unit is to be evacuated in severe storms (and this is part of the requirements for safe operation contained in the Operations Manual). If the Operations Manual does not call for a proper evacuation plan, it is recommended that the unrestricted service vessel design criteria should be for the 100-year return period environmental conditions.

The 1-year, 10-year, and 100-year return period environmental characteristics that may be used for liftboat design and evaluation in the Gulf of Mexico are summarized in Table 1, below, and are produced in graphical form in Figures 29 and 30, eliminating the large steps in wave height in Table 1.

TABLE 1

Environment	*1-year*	*10-year*	*100-year*	*1-year*	*10-year*	*100-year*
Parameter	*water depth < 50'*			*50' < water depth < 100'*		
wind speed	*60 knots*	*78 knots*	*104 knots*	*60 knots*	*78 knots*	*104 kt*
wave height	*14 feet*	*32 feet*	*48 feet*	*20 feet*	*46 feet*	*68 feet*
wave period	*5.5 sec*	*8.3 sec*	*10 sec*	*6.5 sec*	*10 sec*	*12 sec*
current	*1.7 knots*	*2.5 knots*	*> 2.5 knots*	*1.7 knots*	*2.5 knots*	*> 2.5 kt*

This table could be presentaed as a series of curves related to water depth in order to eliminate the large steps, see Figures 29 & 30.

For operation in water depths greater than 100 feet, the wave heights increase, as do typical design periods (but remember that a range of wave periods should always be investigated), the wind speeds remain the same, and the current may be kept as for the 100 ft water depth.

The minimum air gap for design should correspond to the bottom of the hull being at an elevation equal to the maximum elevation of the wave crest above the mean low water level, plus astronomical tide height, plus storm surge height, plus a minimum clearance of 4 feet, or 10% of the combined water heights above mean low water level, if this is greater than 4 feet. This is the ABS requirement (Reference 12) for jack-ups.

The minimum pad penetration into the sea bed for design should correspond to a weak soil. A "10-lb" soil is recommended, 10-lb meaning that the undrained shear strength starts at zero and increases at the rate of 10 psf per foot of depth. In order to achieve a bearing capacity of 300 kips (during preload) a pad with area 260 square feet would need to penetrate approximately 13 feet into such a soil. While this number is typical, a proper penetration analysis should be performed for each vessel, considering the design maximum preload (which is dictated by the fundamental design criterion b).

Structural Response to Environmental Loads

The overall analysis procedure is shown diagrammatically in Figure 5. Important concepts are addressed individually in the following sections, before the complete procedure is assembled.

As a first approximation the liftboat hull may be assumed to be an order of magnitude stiffer than the legs and may be treated as rigid in the initial elevated analysis. With this assumption the global performance of the unit in elevated conditions can be assessed. However, at the detailed design stage the actual hull stiffness characteristics should be determined and proper stress analysis of the combined hull and legs should be undertaken.

The general behavior of liftboats is to sway sideways on their relatively slender legs. Side sway is combined with torsional response about a vertical axis which is normally close to the center of gravity of the vessel. Sway response is both static and dynamic. The hull is deflected laterally to a mean position about which the hull sways at wave frequency. Although the sway response is random, a regular wave analysis can be used to evaluate the maximum values that may be experienced in an irregular sea state. The mean deflection corresponds to static response to the steady wind and mean components of the combined wave-and-current force. The dynamic deflections that occur about the mean position correspond to static-plus-dynamic response to the amplitude of the wave-and-current combined force. The magnitude of the dynamic component is expressed as a dynamic amplification factor, DAF.

If the wave period is much greater than the natural sway period of the liftboat, the DAF will be close to unity, meaning that although the sway response will still be perceptible, occurring at wave frequency, it will not be dynamically magnified. It will normally be necessary to include dynamic analysis in the evaluation of a liftboat's capabilities since liftboats are dynamically sensitive structures.

Dimensions of a typical "generic" liftboat are shown in Figures 1 through 3, taken from Reference 13. Figure 4 comes from the same source and shows a typical existing leg cross section. The most recent liftboats to be built have thicker walls (0.718 inch reported in Reference 3). Note that a single rack is typical on each leg, and it is common for all racks to face in towards the center of the vessel. A few liftboats are built with twin racks, and a few are built with four legs.

Structural Modeling and Leg End Fixity Condition Modeling

Since the hull of the liftboat is modeled (in the first instance) as being rigid, the sway and torsional response to environmental loads is principally a function of leg stiffness, leg mass, hull mass and mass distribution, and where dynamic response is significant, damping. In order to calculate leg stiffness, upper and lower leg fixities must be carefully established.

At the hull the leg is not completely fixed. Vertical reactions are taken by the pinions and the rack at a point between the guides. Horizontal reactions are taken at the upper and lower guides. Between the guides the leg may flex. A detailed explanation of how to handle a simplified structural analysis of these conditions is provided in Appendix 1. Figure 6 illustrates a simplified bending moment, shear force, and applied loads diagram for liftboat legs.

At the sea bed the leg is supported by a foundation pad to which it is welded. The pad is restrained against movement by the seabed soil. This restraint is difficult to calculate but as a first approximation may be modeled as a rotational linear spring. The stiffness of this spring can be found by equating the footing to a disk on an elastic-half space. The soil shear modulus may be defined as a function of the soil undrained shear strength (Reference 14). Detailed guidance is given on this in Appendix 1, page 8, "Calculation of Rotational Stiffness of Footing" and on page 11, "Calculation of Footing Ultimate Moment Capacity". Note that because of the soil stiffness, the bending moment in the leg is not zero at the pad, as can be seen in Figure 6.

Liftboat legs are generally cylindrical but because of the rack(s) the leg structural properties are different in the fore/aft and the lateral directions (as are hydrodynamic drag properties). This difference in structural properties must be accounted for carefully in the structural model since it not only leads to important changes in the overall structural response but it leads also to large changes in the maximum stresses induced in the legs. The sign convention used for wave and wind loading direction is shown in Figure 7.

P-Delta Effect

The P-delta effect, as it applies to liftboats, may be defined as the effect of increased bending moments, and hence stresses, in the liftboat legs as a consequence of the lateral sway deflection of the hull. Figure 8 illustrates the concept of the P-delta effect with a 2-dimensional frame, showing an exaggerated lateral sway through a distance ***delta***. The footing reaction on the left, R2, has been increased and that on the right, R1, has been decreased. The reactions are given by:

R1 = W/2 - W.***delta***/a - P.***L***/a

R2 = W/2 + W.***delta***/a + P.***L***/a

Where:

P	=	applied lateral load to top of frame
W	=	weight of frame (all weight in top for this example)
a	=	distance between (pin-jointed, in this example) supports
L	=	length of legs of frame

At the top of the legs the bending moments are given by:

M1 = P.***L***/2 + R1.***delta***

M2 = P.***L***/2 + R2.***delta***

It can be seen from the preceding equations that the term ***delta*** causes the largest vertical footing reaction to increase further (than would be predicted for a rigid laterally and vertically loaded frame) and causes the smallest vertical footing reaction to decrease further (than would be predicted for a rigid frame) when the horizontal load, P, is applied. It can also be seen that the moment at the top of both legs is increased because of the term ***delta***.

The P-delta effect is most pronounced with large axial loads (large values of W) and with slender flexible legs. The direct consequence of the P-delta effect on the response of a liftboat, is to significantly increase lateral sway, leg bending moments, and leg stresses. The increase is in comparison to those values that would be predicted by analysis procedures that omit consideration of the serious reduction in lateral stiffness caused by axial loading.

Prediction of Secondary Bending Effects

Secondary bending effects are generally not correctly accounted for in popular and well-respected structural analysis computer programs. The so-called P-delta effect is generally regarded as a non-linear effect and precludes the solution to structural response by inversion of a linear stiffness matrix, the most common solution technique adopted in finite element structural programs. The requirement to develop an iterative technique to solve the secondary bending problems associated with liftboat analysis was an original part of the contract for which Reference 13 is the draft final report.

If the leg, or frame, stiffness is calculated without consideration of axial stiffness reductions, the calculation of deflection (as a consequence of a horizontal load) will be underestimated. An iterative procedure can be used to find the final deflected position. The axial load applied at the top of the leg causes a secondary bending moment when the leg is deflected by the horizontal load. This secondary bending moment at the top of the leg itself causes a further deflection of the leg. The leg is then subject to an increased secondary bending moment and deflects further. A method for calculating the secondary bending using this iterative approach has been developed and compared with the direct approach explained in Appendix 1. Deflections predicted by the iterative approach are around 5% greater than those predicted by the direct solution.

The method recommended for liftboat deflection calculation and stress analysis uses equations for leg/hull lateral stiffness which include reduction factors accounting for the influence of axial loads. The solution is direct and does not require iteration. The methods used are fully described in Appendix 1, where several solution techniques for different components of the secondary bending stress problem are explained in detail.

Effective Length, or K-Factors, for Design

There is much debate about what the effective length factor should be for liftboat leg design. The use of the AISC Alignment Chart (Reference 15, page 5-137) to determine effective leg length is not straightforward, but requires careful treatment of the top fixity of the leg in between the guides in the liftboat hull. The effect of guide spacing is generally a much greater source of leg flexibility than is the hull flexibility. In the design of independent leg jack-ups the designer will usually consider the spud can to be pin-jointed to the sea bed at the can tip in order to determine the maximum stress conditions in the leg at the level of the lower guide. The resulting effective length factor is in excess of 2.0 as a consequence of the top leg fixity conditions and the leg does not behave as if it is horizontally guided at the top. This pin-joint assumption may be too conservative for liftboats since their pads provide relatively large rotational restraint to the bottom of the relatively slender legs. In comparison to liftboat legs, jack-up legs are relatively stiff and their spud cans are relatively small compared to liftboat pads. Consequently the relative rotational restraint from the foundation beneath a liftboat leg is much larger than that for a jack-up.

A method for determining the lateral stiffness of liftboats is presented in Appendix 1. An effective length factor for the legs is derived from the leg flexibility. Top fixity, axial load, and bottom fixity all influence the result for lateral stiffness.

As a starting point for liftboat leg design, a K-factor of 2.0 may be assumed.

This value is achieved by finding a rotational spring stiffness at the bottom of the leg, which (when combined with the upper leg fixity, leg properties, and leg length beneath the lower guide) gives a leg flexibility from which an effective K-factor of 2.0 results. This should normally result in a relatively small amount of rotational soil stiffness being predicted. Consequently the bending moment induced at the bottom of the legs should be relatively small.

To ensure that the K-factor of 2.0 is reasonable for the design of a particular liftboat, some consideration to the pad geometry and the relative leg stiffness must be given. For relatively slender legs and extremely large pads, compared to present typical sizes, a K-factor of 2.0 would be too conservative. Conversely, for stocky legs and extremely small pads, compared to present typical sizes, a K-factor of 2.0 would not be large enough and a K-factor equivalent to a pin-joint should be taken. For typical liftboats this would be around 2.20.

The first step is to find the equivalent soil rotational spring that results in a K-factor of 2.0, with the particular liftboat (and loading direction, since the legs are stiffer in the rack direction). Using this spring, the maximum bending moment induced at the bottom of the legs must be found. Then the ultimate moment capacity of the pad on a 10-lb soil (about the weakest axis) should be found, at the preload depth. Calculation of the ultimate bending moment that a particular soil can provide to a particular pad is described in Appendix 1.

It should be checked that the 10-lb soil can provide an ultimate moment (about the weakest pad axis) which is at least 10% greater than the maximum bending moment predicted at the pad.

Although this method is crude, it serves to prevent small pads with very low moment capacity evolving with future liftboats. This is unlikely anyway as it implies smaller pads with larger penetrations and large pad penetrations are not desirable. If the moment capacity of the pads on the 10-lb soil is several times larger than the predicted maximum moment using the rotational spring stiffness for the soil that results in a K-factor of 2.0, then there is some justification for using a larger spring stiffness. This will then reduce the effective length factor. Although the 10-lb soil addresses only cohesive soils, a similar procedure may be followed for cohesionless soils.

Additionally, the designer should consider the rather high stresses that may be induced in the leg at the connection to the pad by strong soils. Although the leg may be able to resist the stresses induced by the maximum design environmental conditions if it is considered fully restrained at the pad, low cycle, high stress-range fatigue damage may lead to premature failure at this location unless special precautions are taken. With the leg fully fixed at the sea bed, an effective length factor of as low as 1.05 may be achieved, depending on the guide spacing and leg design. The possibility for hard spots beneath the corners of pads causing large eccentric loading should also be considered.

Wind Loading

Wind loading analysis should follow the procedures described in the ABS Rules (Reference 12). The drag coefficients used on the leg sections below the hull (in the air gap) and above the hull should be the same as drag coefficients used for wave loading analysis. Due account should be taken of the effect of the rack(s) increasing the drag coefficient in certain directions. Height coefficients and other shape coefficients should be as described in Reference 12.

Care should be taken to estimate the lateral center of wind pressure, in particular when calculating responses induced by wind forces on the beam. The center of pressure is not likely to coincide with the geometric leg center. Therefore, there will usually be a torsional moment induced by the wind load from beam directions. Care should also be taken to correctly account for the longitudinal movement of the center of pressure as the wind direction is varied. The lateral center of pressure for longitudinal wind force components on the hulls and superstructures of liftboats may normally be expected to be on the vessel longitudinal centerline. Note also that the vertical center of pressure varies as the angle of wind attack is varied. Figure 9 shows how the hull and superstructure exposed area of the generic liftboat (detailed in Figures 1 through 4) varies with angle of wind attack. The angular line labeled *plotted points* corresponds to carefully calculated exposed areas at angles from 0 to 180 degrees, plotted at 30 degree increments. The line labeled *approximation used* is a modified sine wave approximation used in a computer program described later. Figure 10 shows similar information on the torsional lever arm variation. Note the sign convention is shown in Figure 7, so that when the wind attack angle is zero, the wind is on the bow and there is no torsional loading. Torsional loading is a maximum when the wind is on the beam. The torsional lever arm is defined as the longitudinal distance between the geometric leg center and the lateral center of area of area exposed to the wind. A positive number indicates the center of area is aft of the geometric leg center. Figure 11 shows the vertical wind load center (for the hull and superstructure) variation with wind attack angle.

When calculating wind loads for the purposes of liftboat design, some allowance should be made for cargo on the deck of the liftboat.

Wave and Current Loading

Wave loads on liftboat legs should be calculated using a wave force, or Morison equation approach.

Normally the wave theory to be used for liftboat analysis should be a shallow water wave theory.

The wave theory, published as a series of graphs, in Appendix A of the ABS Rules (Reference 12), is a suitable wave theory. In Reference 16 it is shown that this theory is generally conservative while following the correct trends associated with water particle kinematics in different water depths, and wave height-period combination regimes.

Figures 12 through 14 show how the ABS shallow water theory results for the generic liftboat differ from Airy wave results as the wave height is varied, with constant (10 second) period in 37 feet water depth. The direction of wave attack (see Figure 7 for sign convention) is 69 degrees for all results presented in Figures 12 through 19, this being perpendicular to the line joining the stern leg and the starboard bow leg, and representing the critical overturning direction. Figures 15 through 17 show the same comparison for the generic liftboat but in 65 feet water depth. The difference is still significant but not as marked as in the 37 ft water depth where at a wave height of 21 feet, the ABS force result is twice that for the Airy wave and the overturning moment is three times greater. In Figure 18, the forces induced on the generic liftboat by a 20 feet high wave in 37 feet of water and in 65 feet of water are compared. It can be seen that at any wave period the same wave height wave in the shallower water induces a greater force on the structure, implying a significantly steeper and harsher wave. The same comparison, but for overturning moments is made in Figure 19, where the ABS wave moments are also compared to the Airy wave induced moments. It is significant to note that the shallow water effects become greater as the wave period becomes longer, since the wave length is also becoming longer and the wave is feeling the bottom more.

The calculation of the combined effect of waves in the presence of current can be made in accordance with the method presented in the Reference 16 which is taken from published guidelines by Det norkse Veritas (Reference 14). This information is reproduced below.

First the inertia force and drag force amplitudes are determined from the ABS method. The drag force is then approximated by a cosine squared function, and the inertia force by a sine function, maintaining correct phase relationships between the two functions. A drag load resulting from a uniform current distribution is then separately calculated. The final drag force is approximated to a cosine squared function about a non-zero mean value.

The *maximum* drag force due to the combined action of waves and current is approximately given by:

$$F_D = F_{DW} + 2(F_{DW} \cdot F_{DC})^{1/2} + F_{DC}$$

Where:

F_D = maximum total drag force
F_{DW} = maximum drag force due to waves
F_{DC} = maximum drag force due to current

The *mean value* of the total drag force is approximately given by:

$$F_{DM} = 2(R)^{1/2}F_{DW} \quad \text{if } F_{DW} > F_{DC}$$
$$F_{DM} = (1 + R)F_{DW} \quad \text{if } F_{DW} < F_{DC}$$

The *amplitude* of the total drag force is given by:

$$F_{DA} = (1 + R)F_{DW} \quad \text{if } F_{DW} > F_{DC}$$
$$F_{DA} = 2(R)^{1/2}F_{DW} \quad \text{if } F_{DW} < F_{DC}$$

Where:

F_{DM} = mean value of total drag force
F_{DA} = amplitude of total drag force
R = F_{DC}/F_{DW}

Calculation of appropriate drag coefficients, taking full account of the effect of the rack(s) is described in Reference 16. Additional information is given below. It should be noted that it may be appropriate to use different drag coefficients on each leg depending upon the direction of the wave and current loading. This may be particularly important where torsional loading is induced by both the wind and the waves.

An equivalent leg diameter should be developed to account for the volume of the rack(s). This may be found as follows:

$$D_{EQ} = \sqrt{(4\,A_T/\pi)}$$

Where:

A_T = Average Cross Section Area
A_T = $A_1 + A_2$
A_1 = leg area excluding rack
A_2 = average rack cross-section area

Drag Coefficients for Design

The drag coefficient for a leg with a double rack, C_{DDR}, may generally be found from the following equation (Reference 14). See Figure 4 for further clarification of the nomenclature.

$$C_{DDR} = C_D + 4\,\Delta/D \cos(90-\alpha)$$

Where:

C_D = drag coefficient for a similar leg without a rack
D = outside diameter of the cylindrical section of the leg
Δ = $a + b/2$
a = height of rack from leg to tooth root (1.5" in Figure 4)
b = height of teeth on rack (4.0" in Figure 4)

α = flow direction relative to the leg
α is zero for flow parallel to the leg diameter with the rack.

The drag coefficient for a leg with a single rack, C_{DSR}, may be found from a similar equation:

$$C_{DSR} = C_D + 8/3\ \Delta/D \cos(90-\alpha)$$

The drag coefficient for a smooth (new) cylindrical leg without a rack shall normally be taken as 0.64. Factors affecting this value include marine growth and other roughness influences, and Reynold's Number.

An alternative formula is given for cylindrical legs with double racks by Shell (SIPM) in Reference 5 and is given below:

$$C_{DDR(Shell)} = C_D + (1.85\ D1/D - C_D) \sin^2 \alpha$$

Where:

D1 = $D + 2\Delta$ (the distance between the mid depth of the racks)

The Shell formula may be modified in a similar manner to that in which the DnV formula has been modified above for the case of a leg with only a single rack. This results in the formula below:

$$C_{DSR(Shell)} = C_D + (0.67 * 1.85\ (D + \Delta)/D - C_D) \sin^2 \alpha$$

For the generic liftboat leg section shown in Figure 4, results for both above formulae are shown in Figure 20, as the angle of wave attack is varied from 0 to 180 degrees. The modified Shell formula gives significantly higher maximum drag coefficient values than the modified DnV formula. The unmodified formulae for double racks show even wider divergence. It is probable that the DnV formula is not conservative, but coupled with the somewhat conservative (Reference 16) ABS shallow water wave theory, probably gives safe results.

Inertia Coefficient for Design

In most design wave cases the hydrodynamic loading on the legs will be dominated by drag forces. However, inertia forces will be important in short period waves. The appropriate inertia coefficient to use for the legs is 2.0, together with the equivalent diameter described above.

Wave Phasing and Other Concerns

The wave loading during the passage of a wave must be accounted for on each leg taking careful account of the wave phase angle at each leg. In short period waves it may be possible to have wave cancellation effects such that one leg is seeing the opposite of the load imposed on the other two legs.

It is not normally considered necessary to calculate loading and response using the relative velocity between the legs and the water particles, accounting for leg movement as the liftboat sways (that is, the sway velocity of the legs may be neglected). However, where the natural sway period is in excess of 3 seconds, and where the wave period of interest is within 25% of the natural sway period, the equivalent linear damping term in the dynamic response calculation may be increased to a maximum of 8% critical. Dynamic response is described later.

It is not considered necessary to account for the vertical hydrodynamic pressure loading on the pads as the wave passes.

Bending Moment Coefficients, Beta and Mu

Figure 6 shows the general form of the bending moment diagram for each leg. The diagram is simplified for the purpose of explaining the coefficients. The simplification is in not showing the distributed wave loads along the leg. Two coefficients may be used, Beta and Mu to perform the analysis in an efficient manner as laid out for jack-ups in Reference 14. Beta determines the fraction of the upper leg bending moment which is reacted by vertical forces in the racks in double rack legs. Beta should be taken as zero in single rack legs. Beta is found from the following equation:

$$\text{Beta} = 1/(1 + G\, A_{Q0}\, d/k_j)$$

Where G is the shear modulus of steel, A_{Q0} is the average shear area of the leg portion within the guides, d is the vertical distance between the guides, and k_j is the jack rotational stiffness (see References 14 & 19 for full description).

Mu determines the bottom leg bending moment and is a function of two other coefficients as shown below:

$$a = A_Q\,(1 - \text{Beta})/A_{Q0}$$

$$i = I\,[1 - \text{Beta}(1 - 3b/d + 3(b/d)^2/2)]/I_0$$

Where I is the average moment of inertia of the leg, A_Q is the average shear area of the leg, I_0 is the average moment of inertia of the leg portion within the guides, and d is the height of the jack support point above the lower guides. To get Mu we have:

$$\text{numerator} = 1 + 2id/3l + 2a\,E\,I/(l\,d\,G\,A_Q)$$

$$\text{denominator} = 1 + 2E\,I/(k_s\,l)$$

$$\text{Mu} = \text{numerator}/\text{denominator}$$

Where *l* is the leg length from the lower guide to the mid-height of the pad and all other terms are defined above (see also Figure 6).

Transverse Stiffness of Liftboat

The transverse overall stiffness of one leg is given by:

$$k = 1/(f_B + f_Q)$$

Where f_B and f_Q are the bending and shear flexibilities of the leg and are given by:

$$f_B = \text{Beta}\, l^3\,[1 - 3\text{Mu}/2(1 + \text{Mu}) + id/l(1 + \text{Mu})]/3EI$$

$$f_Q = l\,[1 + al/d(1 + Mu)]/GA_Q$$

Alternatively, the overall transverse stiffness of one leg may be represented by:

$$k = 3EI/cl^3$$

Where:

$$c = 1 - 3Mu/2(1 + Mu) + id/l(1 + Mu) + 3EI[1 + al/d(1 + Mu)]/l^2GA_Q$$

The transverse stiffness found by this method for the generic liftboat is compared in Appendix 1 with classical solutions (ignoring shear stiffness) from Roark (Reference 17). Comparisons are excellent. The coefficient, c, is used to find an effective length factor (see below).

Before response to loading can be found, the transverse stiffness must be reduced to account for axial leg loads. The first step is to determine the Euler leg load.

Euler Leg Load, P_E and Effective Length Factor

The Euler load, P_E, of a leg is found from:

$$P_E = \pi^2 EI/(Kl)^2$$

Where K is an effective length factor given by:

$$K = 2\sqrt{c}$$

Effective Stiffness Accounting For Axial Leg Loads

For the elevated condition the effective stiffness is taken as:

$$k_e = k\,(1 - P/P_E)$$

Where P is the average axial load on the leg and should include some portion of the leg weight.

Calculation of Liftboat Natural Periods

After leg mass and stiffness properties (including hydrodynamic added mass) have been found, the vessel natural periods in surge, sway, and torsion can be found. Account must be taken of the hull inertia and relative position of the center of gravity position. Values for Mu and Beta both influence natural period results. The closer the natural periods of the vessel get to the wave period, the larger will be the dynamic magnification of the vessel's responses. The boat's natural periods are given by:

$$T_0 = 2\pi\,[m_e/k_e]^{1/2}$$

Where:
k_e = effective stiffness of one leg (defined above)
m_e = effective mass related to one leg

The effective mass for one leg is taken as:

$$m_e = c_1 M_H + c_2 M_L$$

Where:

M_H = total mass of the hull with all equipment and the portions of the legs located above the lower guides
M_L = mass of the portion of one leg located between the lower guides and the top of the pads, including hydrodynamic added mass.
c_1 = 1/n for sway modes
c_1 = $1/n\ (r_0/r)^2$ for torsion mode
c_2 = 0.5 - 0.25Mu
n = number of legs
r = distance from center of legs to hull's cg
r_0 = radius of gyration of the mass M_H with respect to vertical axis through center of gravity

Note that the direction of the applied loading and the relative orientation of the legs and racks may significantly influence the effective stiffness.

Dynamic Amplification Factor (DAF) and Damping

The method for calculating the DAFs may be based upon an equivalent single degree of freedom system.

The dynamic amplification factor is found from:

$$DAF = [(1 - (T_0/T)^2)^2 + (2\ Eta\ T_0/T)^2]^{-1/2}$$

Where T_0 is the vessel natural period and T is the period of the wave.

The above equation is appropriate to response evaluation in long crested regular waves and may be unreasonably conservative in real sea conditions. To account for this, DnV (Reference 14) introduced the concept of a *stochastic dynamic amplification factor*, SDAF. The accepted result of this approach is to compute DAFs with twice the equivalent linear damping term, Eta. This method is recommended in liftboat analysis.

Damping alone limits vessel response values at resonance, where the wave period and the vessel first natural period are coincident. Away from resonance, as is the normal case with storm waves, the damping value is less critical. However, because of the uncertainty in the damping value, it may be useful to examine response with a range of values for Eta. In the absence of better knowledge, a value of:

Eta equals 2% critical damping

is suggested unless the wave period under consideration is within 25% of the liftboat's natural period. In this case response may be violent inducing significant hydrodynamic damping, making Eta equal to as much as 8% critical. A report of recent field measurements (Reference 18) cites a value of as low as 1% critical damping for a Gulf of Mexico jack-up rig. However, the amplitude of responses referred to is also rather low, and hydrodynamic, as well as mechanical (in the area of the guides and jacks) damping may be expected to increase as responses increase.

Static and Dynamic Response Analysis

Having found the environmental loading together with the mass and stiffness properties of the structural model, the static and dynamic responses of the liftboat to the loading can be found. The loading is divided into a mean, or steady part, and an amplitude, or dynamic part. The response is found from the combination of static response to the steady loading and dynamic response to the dynamic loading. The dynamic response is found from multiplying the equivalent static response to the amplitude of the dynamic forces, multiplied by the DAF found above.

Where the DAF is small, the total response is approximately the same as would have been found by static analysis alone. Where the DAF is large, there may be significant differences.

It is important to note that the response and the forcing function (the dynamic component of the wave-current forces) are not necessarily in phase. The phase lag of the response may result in the maximum deflection occurring after the maximum overturning moment. Hence it is sometimes conservative to simply add the maximum additional overturning moment caused by the lateral deflection of the center of gravity of the boat directly to the overturning moment in order to determine the maximum overturning with the P-Delta effect.

If the time history of the applied environmental loading function is very non-sinusoidal there may be reason to suspect that the dynamic response is over-estimated by the simple single-degree of freedom model described above. However, experience shows that the overturning moment in "design wave" conditions for liftboats is normally close to having a sinusoidal variation and there should be few instances where the dynamic results are overly conservative using this approach.

Initial Static Offset

It should be noted that no liftboat is perfect and due allowance should be made for legs not being perfectly straight, the hull not being perfectly level (the level indicators sometimes do not read to better than 0.5 degrees), and the lack of alignment within the guides. DnV (Reference 14) require an offset of 0.005 times leg length extended for lateral hull offset to account for these effects. Shell (Reference 5) specify .003 times leg length extended. Liftboat tolerances are generally greater than those of jack-ups for which the above requirements were evolved and elevating generally takes place faster, with less attention to detail. Hence:

a minimum value for the offset coefficient is recommended to be .005 times leg length extended.

Leg Stress Checks Required

The most important leg stress checks are on the combined axial compression and bending stresses, following ABS requirements (Reference 12). The location of maximum leg stress is usually at the level of the lower guide. At this point the leg bending moment is a maximum as shown in Figure 6. Allowable axial stresses, F_a, are computed which are to be the least of:

a) *yield stress divided by appropriate factor of safety*
b) *overall buckling stress divided by appropriate factor of safety*
c) *local buckling stress divided by appropriate factor of safety*

The appropriate factors of safety for a) and c) are generally 1.25, as they represent combined (live) loadings. The factor of safety for b) is either 1.25 or 1.44, depending on the slenderness ratio, the yield stress, etc. The overall buckling stress is well-defined in Reference 12, although the local buckling stress must be found from another source. API RP 2A (Reference 8) is used to find elastic and inelastic local buckling stresses.

Note that the latest revision of the ABS unity check requirements is contained in Notice No. 1, effective May 1989, applicable to the 1988 MODU Rules (Reference 12). In this version a coefficient C_m is introduced when f_a/F_a exceeds 0.15, bringing the stress check more closely in line with AISC and API similar unity stress checks.

When f_a/F_a is less than or equal to 0.15, the required unity stress check is:

$$f_a/F_a + f_b/F_b \leq 1.0$$

When f_a/F_a is greater than 0.15, the required unity stress check is:

$$f_a/F_a + C_m f_b/((1 - f_a/F'_e)F_b) \leq 1.0$$

Where:

f_a = *actual axial stress*
F_a = *allowable axial stress*
f_b = *actual bending stress*
F_a = *allowable bending stress*

F'_e = $12\pi^2 E/(23(Kl/r)^2)$

F'_e is the ABS/AISC-defined Euler buckling stress and may be increased under ABS rules by 1/3 for combined loadings.

K is the effective length factor.

C_m is a coefficient which relates to joint translational freedoms. For liftboats this coefficient is to be taken as 0.85.

Limiting leg stress conditions may also be caused by vessel first order wave motions when in transit. Leg impact loads caused by the pads striking hard sea beds may also represent limiting leg stress conditions and should be addressed both in design, evaluations performed for Coast Guard requirements, and should be addressed in the rig Operations Manual, where limiting conditions for moving location should be defined. The ABS (Reference 12) guidelines for leg strengths required for jack-ups in transit are not well suited to liftboats. However this matter is beyond the scope of this paper.

Consideration must also be given to fatigue damage.

For new designs a fatigue analysis should be performed.

The most fatigue prone location in the leg is at the connection to the mat. At this point the bending stresses may be larger than those at the level of the lower guide in most conditions, since for small strains in most soils the pad will be close to behaving as if it was fully-fixed.

Implementation of Response Analysis on a PC (Personal Computer)

Because of the number of load cases that must be investigated in order to determine the adequacy of any liftboat design, a computer program is necessary, both in design and in the retrospective analysis of liftboats that must now obtain inspection certificates from the Coast Guard. Such a program has been developed by the author within the environment of Lotus Symphony, a spreadsheet program from the Lotus Corporation. This program, STA LIFTBOAT, is written in the macro language of Symphony. Run times of less than 30 seconds are achieved on a 386-based PC.

Example Liftboat Elevated Analysis Results

The generic liftboat described in Figures 1 through 4 is used as an example of the analysis procedure. Additional hull depth is added and the maximum displacement is defined as being 900 kips. The leg steel yield strength is defined as being 60 ksi and the wall thickness is increased from 0.5 inches to 1.0 inches. The elevated center of gravity of the vessel is to be brought to the geometric leg center when severe weather is anticipated. The air gap is also to be brought to a within a range which is to be defined in the Operations Manual. The minimum air gap is to satisfy the rule stated earlier. *The maximum air gap for storm survival may also be limited.*

The principal vessel characteristics are given in Table 2 below.

TABLE 2: Example Liftboat Characteristics

VARIABLE	Original	New
LOA	90.0 ft	90.0 ft
Maximum Beam	60.0 ft	60.0 ft
Depth	8.0 ft	9.5 ft
Draft (approximate)	3.5 ft	4.7 ft
Distance between forward leg centers	50.0 ft	50.0 ft
Distance from fwd. leg centers to aft leg center	66.0 ft	66.0 ft
LCG (fwd. of stern leg center when elevated in storm)	40.0 ft	44.0 ft
TCG (on vessel centerline)	0.0 ft	0.0 ft
Displacement (max)	650.0 kips	900.0 kips
Lightship weight	525.0 kips	700.0 kips
Leg Length	130.0 ft	130.0 ft
Leg Diameter (O.D.)	42.0 in	42.0 in
Leg Wall Thickness	0.5 in	1.00 in
Yield strength of steel in legs	50.0 ksi	60.0 ksi

The environmental conditions selected correspond to the 1-year return period conditions defined earlier in Table 1, for water depths in the range 50 to 100 feet. The selected water depth for the analysis, which includes predicted increases due to tides at the location, is 65 feet. A relatively large variable load is defined of 200 kips, resulting in a total vessel weight equal to its maximum displacement of 900 kips. This large weight gives the largest stabilizing moment to resist overturning, but is detrimental in other ways. An appropriate drag coefficient for each leg is used, depending upon the wave direction considered. For this example results for a beam direction of loading only are presented. Several other directions, several other variable load conditions, and several other wave periods must be evaluated before the design can be pronounced satisfactory.

The resulting wave and current forces and moments applied to the legs, together with total forces and moments including wind loads are shown in Figures 21 and 22. Note that the wave length and direction selected result in different phase angles for loads on the legs.

The drag and inertia forces on leg 1 are shown separately on Figure 23. Note that the inertia force is virtually symmetric about zero, going positive and negative at a 90 degree phase angle to the drag force. However, largely because of the current, the drag force is almost always positive, so that the resulting combined force is not symmetric about the zero force axis.

The wave phasing at the legs is shown schematically in Figure 24. Sinusoidal profiles are drawn for simplicity. The actual wave profiles may be very sinusoidal, depending on the water depth and the wave height and period selected.

In Figure 25 the DAF plots for the liftboat are shown for three different values of damping, 1%, 2%, and 4% of critical. The "new" leg design with 1.0" wall thickness has a natural period of 3.7 seconds, while the "original" leg design, with 0.5" wall thickness has a natural period of 5.2 seconds under the same conditions. In the 6.5 second waves, the response of the thinner walled leg design was subject to significant dynamic amplification. The DAF reduced from 2.6 to 1.5 as a consequence of the thicker legs increasing the stiffness of the vessel. Table 3 gives the intermediate input data for the run with the 0.5" leg. The almost identical Table 4 shows the intermediate input data for the run with the 1.0" leg.

TABLE 3

STA LIFTBOAT v1.0 June 1990		08/12/90	Date of run
FINAL PROCESSING FILE		Boat Name: STA LIFT1	
Run Ref.:	65ft, 20/6.5/1.7 Beam Loading		<appears on graphs
Press Alt-S to save graphs, Alt-A for RESULTS SUMMARY, Alt-B for stress check			
Press Alt-I to print this input, Alt-R for results, Alt-C for stress checks			
EDIT USER DEFINED VARIABLES			
4248000	Young's Modulus, leg steel (ksf)	1.93	K-equivalent
1	nat.period multiplier (norm.=1; no dyn.=.01)		
60	yield stress for leg steel	1	add.mass coef.(norm.=1)
2	accept calc. wt/ft (1=no, 2=yes)	5	VCG excluding legs (ft)
2	accept hull gyrad. (1=no, 2=yes)	15	weight of 1 pad (kips)
22	coef.on su to get soil G modulus	0.285	calculated leg kips/ft
160	su, soil und.shear str. (psf)	30.18	calculated hull gyrad.
13326.821	ks, calc.rot.stiff.soil (kip-ft/rad)	0.28	USER SPEC.leg kips/foot
8.00E+05	kj, rot.stiff.jack/hull (kip-ft/rad)	30	USER SPEC. gyrad. (ft)
10.49	k, calc.overall leg stiff.(kips/ft)	0.00	Beta, calculated
0.005	Ke0, horiz.offset coef.	0.16	Mu, calculated
0.64	cylinder drag coef.(w/marine growth)	2	total damping (% crit.)
0.00	marine growth thickness (inches)	0	Beta maximum
INPUT STRUCTURAL LEG DATA BELOW:			
3	VCG lower guide (ft)	1	geometry select.switch
42	leg OD (in)	14	d, guide spacing (ft)
0.5	wall thickness (in)	7	b, jack vcg (ft)
4	rack width (in)	4.5	h, jack support spacing (ft)
4	rack height to top teeth (in)	25	pad length (ft)
1.5	rack height to bot. teeth (in)	10	pad width (ft)
4.5	stiffener area in sqin	1.5	pad 1/2 height (ft)
0.04	leg wt.factor for appendages, etc	1	1 OR 2 RACK SWITCH
2ND Title for drag coefficient graph >>>>		LIFTBOAT 42 INCH DIAMETER LEG	

Note that the K-factor is slightly different from Table 3 to Table 4. This is because the soil strength has not been changed, but the leg strength has. Consequently a smaller K-factor results, together with a significantly increased value for Mu.

TABLE 4

STA LIFTBOAT v1.0 June 1990		08/12/90	Date of run
FINAL PROCESSING FILE		Boat Name: STA LIFT1	
Run Ref.:	65ft. 20/6.5/1.7 Beam Loading		<appears on graphs
Press Alt-S to save graphs, Alt-A for RESULTS SUMMARY, Alt-B for stress check			
Press Alt-I to print this input, Alt-R for results, Alt-C for stress checks			
EDIT USER DEFINED VARIABLES			
4248000	Young's Modulus, leg steel (ksf)	2.01	K-equivalent
1	nat.period multiplier (norm.=1; no dyn.=.01)		
60	yield stress for leg steel	1	add.mass coef.(norm.=1)
2	accept calc. wt/ft (1=no, 2=yes)	5	VCG excluding legs (ft)
2	accept hull gyrad. (1=no, 2=yes)	15	weight of 1 pad (kips)
22	coef.on su to get soil G modulus	0.510	calculated leg kips/ft
160	su, soil und.shear str. (psf)	30.18	calculated hull gyrad.
13326.821	ks, calc.rot.stiff.soil (kip-ft/rad)	0.28	USER SPEC.leg kips/foot
8.00E+05	kj, rot.stiff.jack/hull (kip-ft/rad)	30	USER SPEC. gyrad. (ft)
20.18	k, calc.overall leg stiff.(kips/ft)	0.00	Beta, calculated
0.005	Ke0, horiz.offset coef.	0.10	Mu, calculated
0.64	cylinder drag coef.(w/marine growth)	2	total damping (% crit.)
0.00	marine growth thickness (inches)	0	Beta maximum
INPUT STRUCTURAL LEG DATA BELOW:			
3	VCG lower guide (ft)	1	geometry select.switch
42	leg OD (in)	14	d, guide spacing (ft)
1	wall thickness (in)	7	b, jack vcg (ft)
4	rack width (in)	4.5	h, jack support spacing (ft)
4	rack height to top teeth (in)	25	pad length (ft)
1.5	rack height to bot. teeth (in)	10	pad width (ft)
4.5	stiffener area in sqin	1.5	pad 1/2 height (ft)
0.04	leg wt.factor for appendages, etc	1	1 OR 2 RACK SWITCH
2ND Title for drag coefficient graph >>>>		LIFTBOAT 42 INCH DIAMETER LEG	

Tables 5 and 6 contain the Results Summary for each of the two runs. It is noted that the consequence of doubling the wall thickness is to double the lateral stiffness, which goes from 31 kips per foot to 61 kips per foot. However, because of dynamics, the maximum hull deflection is greater affected and reduces from 3.93 feet to 1.47 feet (including the static offset the maximum deflection goes from 4.39 feet to 1.92 feet when the wall thickness is doubled) A dramatic improvement in the ABS unity stress checks also occurs. The stress check for the stern leg (leg 2) reduces from an unacceptable 3.28 to an acceptable 0.83. No graphical results, apart from DAFs in Figure 25, are given for the 0.5" wall thickness design, as it has very poor performance characteristics and cannot survive the 1-year storm criteria.

The effect of response on the 1.0" wall thickness design is clearly seen in Figure 26 where the two solid lines show the difference between the applied overturning moments and the "corrected" overturning moments, which include the increase in overturning as a consequence of the P-delta effect. In this example the overturning moment is increased from 6032 foot-kips to 8348 foot-kips, an increase of 38%.

The predicted factor of safety against overturning is seen in Table 6 to be 1.44, which is satisfactory, but additional critical loading directions must also be investigated.

Appendix 2 contains an extract from the User's Manual for STA LIFTBOAT (Reference 19) and provides an explanation of all the terms given in Tables 5 and 6. For a fuller explanation of Tables 3 and 4, the reader is referred to Reference 19.

TABLE 5

STA LIFTBOAT v1.0 June 1990

08/12/90 Date of this run

TABLE OF RESULTS Run Ref.: 65ft, 20/6.5/1.7 Beam Loading

STA LIFTBOAT v1.0 June 1990			Boat Name: STA LIFT1		
INPUT SUMMARY			LIFTBOAT TYPE 1	STA RIG # # N	
Wave height	20	feet	Tidal current	1.7	knots
Wave period	6.5	seconds	Wind driven curr.	0	knots
Water depth	65	feet	Pad penetration	3	feet
theta, wave dirn.	90	degrees	Air gap	20	feet
Wind force	COMPUTE	BELOW	Wind speed	60	knots
Leg equiv.av.dia.	3.51	feet	Av. leg mass coef.	2	coef.
Damping ratio	2	% crit.	Av. leg drag coef.	0.74	coef.
Total weight	900	kips	Beta, top fixity	0.00	ratio
ks, soil stiff.	1.33E+04	kipft/rad	Mu, bottom fixity	0.16	ratio
su, soil und.ss.	160	psf	kj, JackHull stiff	8.00E+05	kipft/rad
Gfactor on su	22	coef.	Equiv. pad radius	8.92	feet
LCG	22	feet	TCG	0	feet
Ke0, Offset coef.	0.005	LegLength	VCG excldng. legs	5	feet
Fwd-aft leg dist	66	feet	Fwd leg spacing	50	feet
LegLength extend.	91	feet	Total leg length	130	feet

STA LIFTBOAT v1.0 June 1990			*Legs are dry internally*		
RESULTS SUMMARY			LIFTBOAT TYPE 1	STA RIG # # N	
Pad1 bef.env.loads	258	kips	Pad2 bef.env.loads	258	kips
Pad3 bef.env.loads	258	kips	Weight - buoyancy	774	kips
Av.leg buoyancy	42	kips	Total buoyancy	126	kips
Lateral Stiffness	31	kips/ft	lateral x-stiff.	29	kips/ft
Wind force	27	kips	lateral y-stiff.	31	kips/ft
Max wav-cur.force	59	kips	Mean wav-cur.force	23	kips
Wind O/T moment	2684	ft-kips	Max. total force	86	kips
Amp.wav/cur.O/Tm	2064	ft-kips	Mean wav-cur.O/Tm	1284	ft-kips
Tnxx sway period	5.38	seconds	Max.apparent O/Tm	6032	ft-kips
Tnyy sway period	5.15	seconds	Max torsion mom.	481	ft-kips
Nat. tor. period	4.37	seconds	DAF	2.64	ratio
Mean hull defln.	1.45	feet	Hull defln. amp.	2.27	feet
Max hull defln.*	3.93	feet	Offset+defln.**	4.39	feet
Uncorr.stab.mom.	12058	ft-kips	Euler leg load	921	kips
Corr.stab.mom.	6973	ft-kips	Max. base shear	145	kips
Max.Up.guide reac.	302.3	kips	Max.low.gde.reac.	344	kips
Max.equiv.top load	123.71	kips	Max.horiz.SC.reac.	41.24	kips
BM.pad.max.w/o.PD.	655	ft-kips	BM.hull max.w/oPD.	2636	ft-kips
PDelta leg BM.max	2293	ft-kips	BM.hull max. w.PD.	4929	ft-kips
PadMax.ld.uncorrd.	379	kips	PadMin.ld.uncorrd.	137	kips
PadMax.ld.corrected	523	kips	PadMin.ld.corrected	-7	kips
Pad mean angle	1.0208	degrees	Pad max.angle	2.8146	degrees
Max.OT w/o PDelta	9424	ft-kips	Max.OT.mom.w.PD	12457	ft-kips
Max.hull ax.F1,F3	293.8	kips	Static offset **	5.46	inches
Max.hull ax.F2	269.1	kips	K-Equivalent	1.93	coef.
max fb, legs 1,3	67.33	ksi	Uncorr. O/T SF	2.00	ratio
max fb, top leg 2	88.49	ksi	Corrected O/T SF	0.97	ratio
max fa, legs 1,3	3.88	ksi	DnV O/T Safety F.	0.74	ratio
max fa, top leg 2	3.55	ksi	K=2 Unity chk.legs1,3	2.98	ratio
Hull max.shr.str.	4.54	ksi	K=2 Unity chk.leg2	3.47	ratio
fa/Fa ABS leg 2	0.45	ratio	K-equiv.Un.chk.legs1,3	2.79	ratio
fb/Fb ABS leg 2	1.95	ratio	K-equiv.Un.chk.leg2	3.28	ratio

TABLE 6

STA LIFTBOAT v1.0 June 1990

08/12/90 Date of this run

TABLE OF RESULTS Run Ref.: 65ft, 20/6.5/1.7 Beam Loading

STA LIFTBOAT v1.0 June 1990			Boat Name: STA LIFT1		
INPUT SUMMARY			LIFTBOAT TYPE 1	STA RIG # # N	
Wave height	20	feet	Tidal current	1.7	knots
Wave period	6.5	seconds	Wind driven curr.	0	knots
Water depth	65	feet	Pad penetration	3	feet
theta, wave dirn.	90	degrees	Air gap	20	feet
Wind force	COMPUTE	BELOW	Wind speed	60	knots
Leg equiv.av.dia.	3.51	feet	Av. leg mass coef.	2	coef.
Damping ratio	2	% crit.	Av. leg drag coef.	0.74	coef.
Total weight	900	kips	Beta, top fixity	0.00	ratio
ks, soil stiff.	1.33E+04	kipft/rad	Mu, bottom fixity	0.10	ratio
su, soil und.ss.	160	psf	kj, JackHull stiff	8.00E+05	kipft/rad
Gfactor on su	22	coef.	Equiv. pad radius	8.92	feet
LCG	22	feet	TCG	0	feet
Ke0, Offset coef.	0.005	LegLength	VCG excldng. legs	5	feet
Fwd-aft leg dist	66	feet	Fwd leg spacing	50	feet
LegLength extend.	91	feet	Total leg length	130	feet

STA LIFTBOAT v1.0 June 1990			*Legs are dry internally*		
RESULTS SUMMARY			LIFTBOAT TYPE 1	STA RIG # # N	
Pad1 bef.env.loads	258	kips	Pad2 bef.env.loads	258	kips
Pad3 bef.env.loads	258	kips	Weight - buoyancy	774	kips
Av.leg buoyancy	42	kips	Total buoyancy	126	kips
Lateral Stiffness	61	kips/ft	lateral x-stiff.	58	kips/ft
Wind force	27	kips	lateral y-stiff.	61	kips/ft
Max wav-cur.force	59	kips	Mean wav-cur.force	23	kips
Wind O/T moment	2684	ft-kips	Max. total force	86	kips
Amp.wav/cur.O/Tm	2064	ft-kips	Mean wav-cur.O/Tm	1284	ft-kips
Tnxx sway period	3.76	seconds	Max.apparent O/Tm	6032	ft-kips
Tnyy sway period	3.67	seconds	Max torsion mom.	481	ft-kips
Nat. tor. period	3.13	seconds	DAF	1.47	ratio
Mean hull defln.	0.75	feet	Hull defln. amp.	0.65	feet
Max hull defln.*	1.47	feet	Offset+defln.**	1.92	feet
Uncorr.stab.mom.	12058	ft-kips	Euler leg load	1631	kips
Corr.stab.mom.	10256	ft-kips	Max. base shear	103	kips
Max.Up.guide reac.	187.1	kips	Max.low.gde.reac.	217	kips
Max.equiv.top load	88.91	kips	Max.horiz.SC.reac.	29.64	kips
BM.pad.max.w/o.PD.	272	ft-kips	BM.hull max.w/oPD.	2055	ft-kips
PDelta leg BM.max	826	ft-kips	BM.hull max. w.PD.	2881	ft-kips
PadMax.ld.uncorrd.	379	kips	PadMin.ld.uncorrd.	137	kips
PadMax.ld.corrected	429	kips	PadMin.ld.corrected	87	kips
Pad mean angle	0.5928	degrees	Pad max.angle	1.1714	degrees
Max.OT w/o PDelta	6992	ft-kips	Max.OT.mom.w.PD	8348	ft-kips
Max.hull ax.F1,F3	273.3	kips	Static offset **	5.46	inches
Max.hull ax.F2	248.6	kips	K-Equivalent	2.01	coef.
max fb, legs 1,3	23.21	ksi	Uncorr. O/T SF	2.00	ratio
max fb, top leg 2	26.81	ksi	Corrected O/T SF	1.44	ratio
max fa, legs 1,3	1.96	ksi	DnV O/T Safety F.	1.47	ratio
max fa, top leg 2	1.78	ksi	K=2 Unity chk.legs1,3	0.78	ratio
Hull max.shr.str.	1.56	ksi	K=2 Unity chk.leg2	0.82	ratio
fa/Fa ABS leg 2	0.22	ratio	K-equiv.Un.chk.legs1,3	0.78	ratio
fb/Fb ABS leg 2	0.56	ratio	K-equiv.Un.chk.leg2	0.83	ratio

Figure 27 shows the time histories of vertical reaction at each of the liftboat pads. These reactions are in response to the loads shown in Figures 21 and 22 (for the 1.0" wall thickness design). Note that reactions shown with light lines are calculated for a rigid structure. The reactions shown with heavy lines are calculated with proper account for response. The differences are significant for the two forward legs. The stern leg sees no pad reaction variation in this case, as the loading is directly on the beam.

Figure 28 shows the sway response time history together with the time history of the (applied) overturning moment. In this case the applied moment appears reasonably sinusoidal and the sinusoidal response assumptions of the simple dynamic model are therefore valid. The two response lines on Figure 28 are for response about a non-offset initial position and for response about an initial position which was offset by .005 times the leg length beneath the hull.

Preload Requirements

In two other runs the maximum pad vertical reactions for the environmental conditions selected were established. The critical direction is perpendicular to the line joining the stern leg and one of the bow legs, with the remaining bow leg leeward, (110 degrees, see Figure 7). The maximum pad reaction is 438 kips, and this sets the minimum preload required. Each bow leg must be loaded to 438 kips during the preload operation if the preload is to be greater than the maximum design storm load. The stern leg has a lower preload requirement.

In a 10-lb soil a preload of 438 kips will cause these pads to penetrate around 17 feet. This is significantly greater than the 3 feet used for these runs.

Conclusions From Example Analysis

The generic liftboat with the 1.0" wall thickness legs and the weight as in Table 2, just about meets the 1-year return period environmental conditions in 65 feet of water. However the runs reported in this paper were performed with only 3 feet of pad penetration. After the necessary preload was determined (for that penetration) a penetration analysis in the 10-lb soil indicated that around 17 feet of pad penetration would occur with that preload.

Subsequent runs identified that the "new" vessel cannot survive the 20 foot high, 6.5 second wave with maximum variable load and 17 feet of pad penetration in 65 feet of water. However this wave corresponds to the 100 foot water depth wave height. Using Figures 29 and 30, the 65 foot 1-year return period wave is found to have a 16 foot height and a 6 seconds period. If the variable load is reduced by 100 kips, the new design just meets the minimum criteria for survival of the 1-year return period environmental conditions in 65 feet of water, with 17 feet of pad penetration, and 20 feet of air gap.

Concluding Remarks and Recommendations For Treatment of Existing Liftboats

Liftboats have emerged as a new and valuable class of vessel during the last two decades. However, they have a rather poor accident record, partly as a consequence of not being required to meet any particular design criteria.

Now that liftboats are to be inspected vessels, designed and built with Coast Guard approval, an opportunity exists to define the criteria that should be used for their design with the special nature of liftboat operations in mind. The Coast Guard have decided to issue "restricted" and "unrestricted" licenses for liftboats, but have not firmly decided upon the design criteria to be used for the two different categories.

This paper recommends that in order to receive a restricted license a liftboat should be able to at least withstand environmental conditions with a 1-year return period probability in the elevated condition. If the vessel is to be issued with an unrestricted license, this paper recommends that the environmental conditions for design should have a 10-year return period in the Gulf of Mexico, provided that the vessel Operations Manual requires evacuation in the event of a hurricane. If the vessel is not to be evacuated in severe conditions, it should be able to withstand the 100-year return period environment.

Requirements for afloat stability and seakeeping have not been addressed in this paper, but are considered vital to liftboat design. Similarly, the requirements for crew training and the safe ***operation*** of liftboats have not been addressed (other than to define minimum preload requirements) but these too are considered vital to liftboat vessel and crew/passenger safety.

Environmental conditions corresponding to 1-year, 10-year, and 100-year return period probabilities are defined for the purpose of liftboat design for the Gulf of Mexico. These environmental criteria follow the accepted API methodology for linking wave heights to water depth and are summarized in Figures 29 and 30, as well as in Table 1.

Because the analysis procedures necessary for liftboats in the elevated condition are unusual in comparison to other boats and other offshore fixed structures (generally only jack-up rigs require similar procedures) this paper details several of the most important analysis procedures necessary for liftboats. Secondary bending stresses in the slender legs as a consequence of the lateral deflections of the hull, normally increased by dynamic amplification, are particularly important.

Much debate in industry has centered upon the appropriate effective length, or K-factor, to be used for liftboat design. This paper recommends that a K-factor of 2.0 is generally to be used. Additionally the paper describes in detail the structural and geotechnical assessments that can be made to reduce (or increase) this number, depending upon the pad geometry and leg stiffnesses of a particular vessel.

The ABS safety factor for overturning for jack-ups (Reference 12) of 1.1, and the ABS unity stress checks for the legs are recommended, as is the ABS requirement for preloading, with the proviso that if the storm load (vertically) on any pad exceeds the preload, the further penetration of the pad is acceptably small.

The importance of fatigue life evaluation for the connection between the bottom of the leg to the pad is emphasized. Failure of this connection would be potentially catastrophic and it is subject to relatively high stress ranges in relatively mild conditions.

Leg structural design to accommodate stresses induced by vessel motions while in transit and pounding on the sea floor when coming onto (or leaving) location are mentioned but not fully addressed.

A method to assess the design pad penetration into the sea floor is recommended. This method is based upon considering a 10-lb soil for the design case. The Operations Manual would be expected to limit operations to shallower water depths if softer soil was to be sat upon. Conversely, if operations in a location with strong soil were anticipated, a deeper water depth would be permitted in the Operations Manual.

If an existing liftboat cannot meet the 1-year return period environmental conditions in the elevated condition (satisfying all the necessary structural criteria in this paper) it is recommended that it not be issued a Certificate of Inspection by the Coast Guard. Options exist to downgrade the water depth capability (which must be clearly stated in the Operations Manual) or to modify the vessel and/or its method of operation.

If an existing vessel is limited by pre-load capabilities, the preload capacities may be increased (or the water depth capability may be reduced).

If an existing vessel is limited by an inadequate overturning safety factor, the stabilizing moment may be increased by carrying additional elevated ballast. However, the leg stresses and preload requirements must still be satisfied. Alternatively the water depth capability for the rig may be reduced. The possibility for flooding the legs may be examined.

If an existing vessel is limited by leg stresses, either stronger legs are required or the water depth range for the vessel may be reduced.

References

1. Barrett, M., *Work Boats With Legs* Work Boat Magazine, January/February, 1990

2. Brewington, R. et al, *Liftboat Operations and Stability, Student Workbook,* July, 1990, available from Houston Marine Training Services and Det norske Veritas, 1325 South Dairy Ashford, Houston, TX 77077

3. Piatt, C., *First Certifiable Liftboat*, Work Boat Magazine, May/June, 1990.

4. Stewart, W.P., White, R., Rapoport, V., Devoy, D., *On-Bottom Stability of Jack-Ups*, Paper No. OTC 6125, Offshore Technology Conference, Houston, May, 1989.

5. Shell International Petroleum Maatschappij B.V. *Practice For The Site-Specific Assessment of Jack-Up Units*, May, 1989, revised 1990, available from SIPM B.V., The Hague, The Netherlands.

6. Sharples, B.P.M., Trickey, J.C., Bennett, W.T., *Risk Analysis of Jack-Up Rigs*, The Jack-Up Drilling Platform, Design Construction, Operation, September, 1989, London, England.

7. *Telephone conversation* between J. Stiff, Noble Denton & Associates, Inc., Houston, and the author, August 8, 1990.

8. American Petroleum Institute, *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms*, RP 2A, 18th Edition, September, 1989.

9. Simiu, E.., and Scanlan, R.H., *Wind Effects on Structures*, 2nd Edition, published by John Wiley and Sons, New York, 1986.

10. American Petroleum Institute, *Recommended Practice for Planning, Designing and Constructing Tension Leg Platforms*, RP 2T, 1st Edition, April, 1987.

11. Bea, R.G., Lai, N.W., Niederoda, A.W., and Moore, G.H., *Gulf of Mexico Shallow-Water Wave Heights and Forces*, Paper No. OTC 4586, Offshore Technology Conference, Houston, May, 1983.

12 American Bureau of Shipping, *Rules for Building and Classing Mobile Offshore Drilling Units*, 1988, with Notice No.1, May 1989, and Notice No. 2, May, 1990, available from ABS, Paramus New Jersey.

13. Stewart, W.P., *Liftboat Leg Structural Analysis*, Draft Final Report prepared for US Coast Guard Research and Development Center, Groton, CT, July, 1990.

14. Det norske Veritas, *Strength Analysis of Main Structure of Self Elevating Units*, Classification Note 31.5, May, 1984 (under revision) available from DnV US Office, 1325 South Dairy Ashford, Houston, TX 77077.

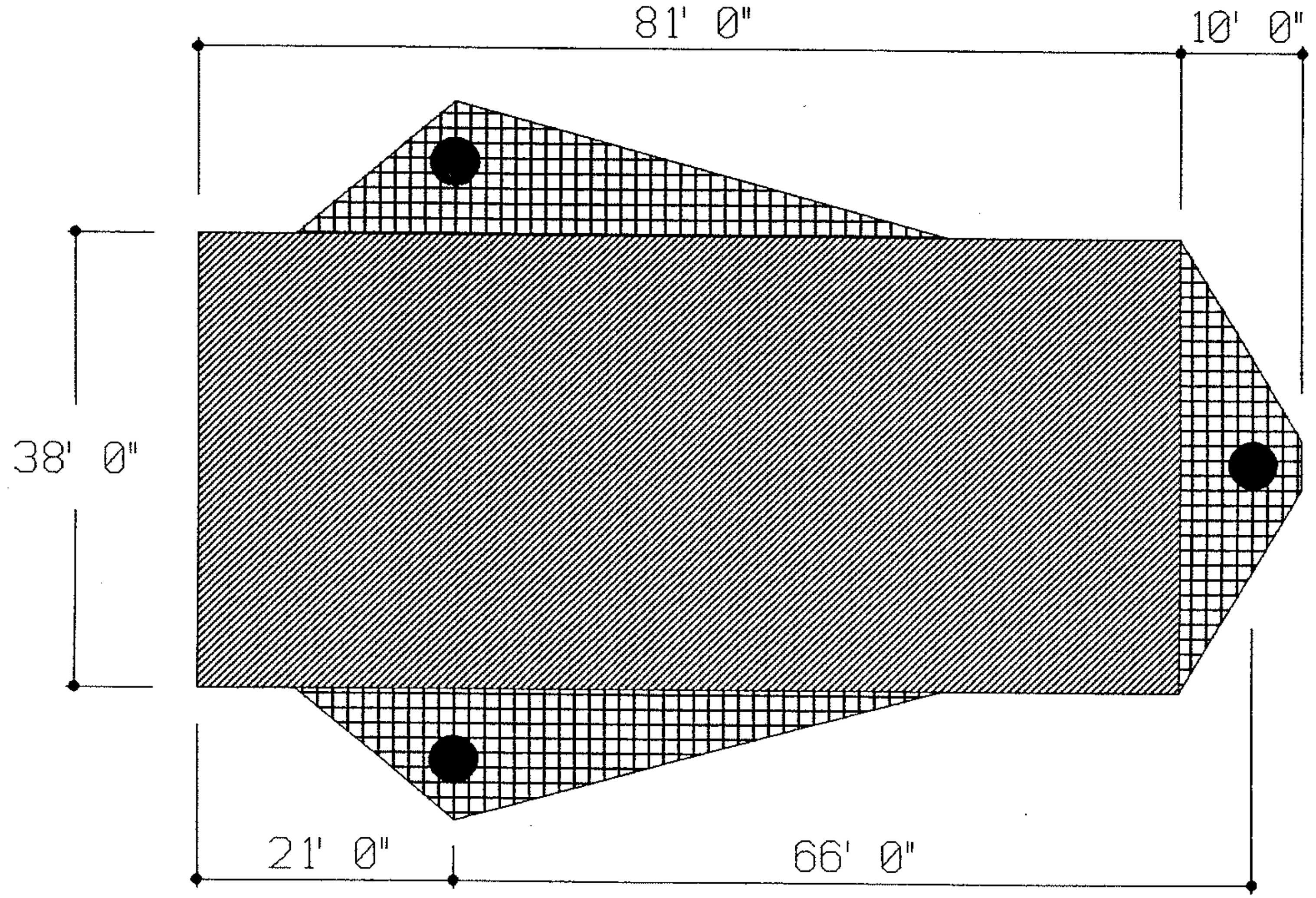
15. American Institute of Steel Construction, Inc., *Manual of Steel Construction, Allowable Stress Design*, Ninth Edition, 1989, available from AISC Chicago, IL.

16. Stewart, W.P., *Liftboat Leg Structural Analysis*, Interim Report prepared for US Coast Guard Research and Development Center, Groton, CT, February, 1990.

17. Roark, R.J., and Young, W.C.., *Formulas for Stress and Strain*, Fifth Edition, McGraw-Hill Book Company, 1975.

18. Brekke, J.N., Murff, J.D., Campbell, R.B., and Lamb, W.C., *Calibration of Jack-Up Leg Foundation Model Using Full-Scale Structural Measurements*, OTC 6127, Houston, TX, May 1989.

19. Stewart Technology Associates, *STA LIFTBOAT Release 1.0*, User Manual for STA LIFTBOAT, June, 1990, available from STA, 5011 Darnell, Houston, TX, 77096.

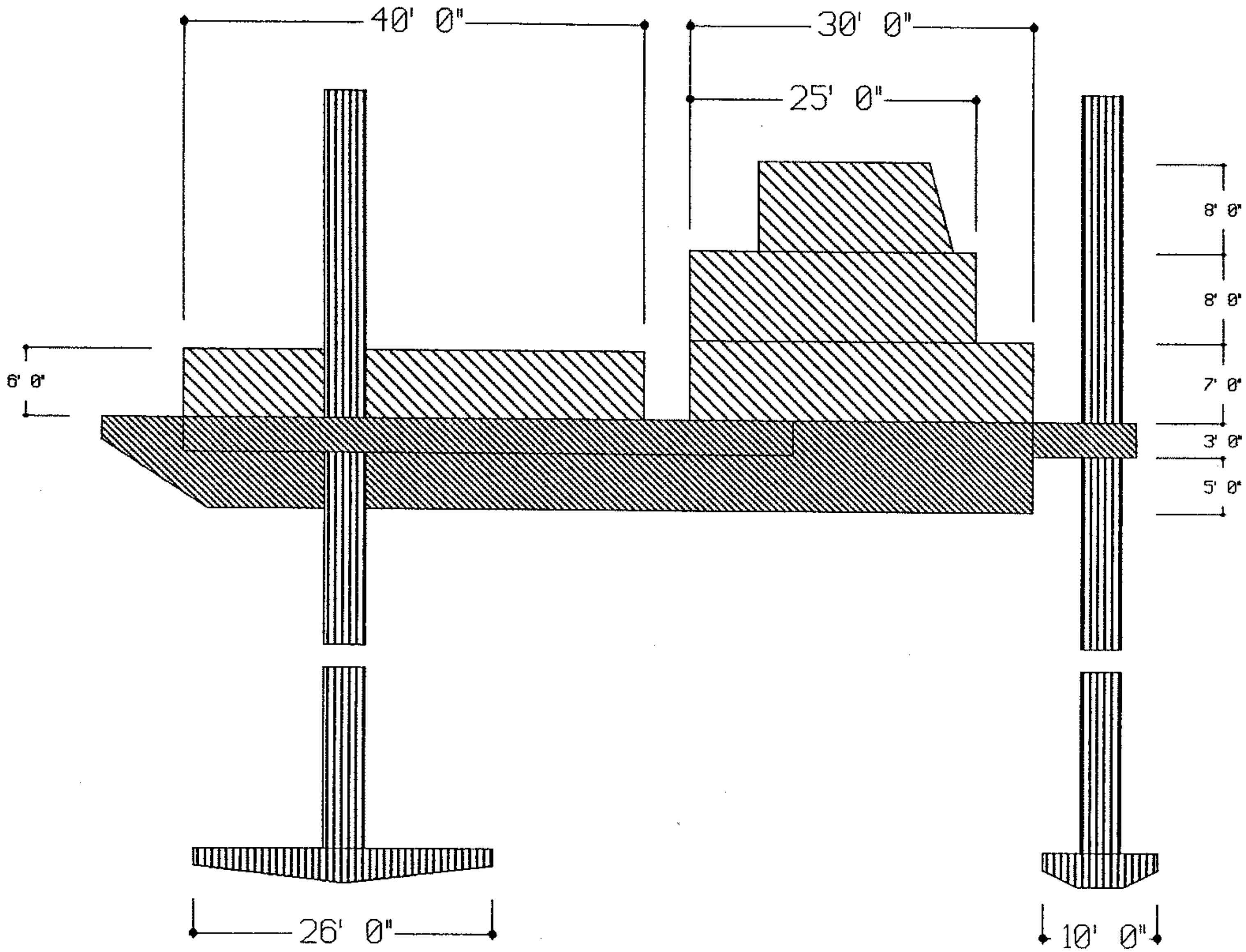


GENERIC LIFTBOAT - PLAN VIEW

STEWART TECHNOLOGY ASSOCIATES

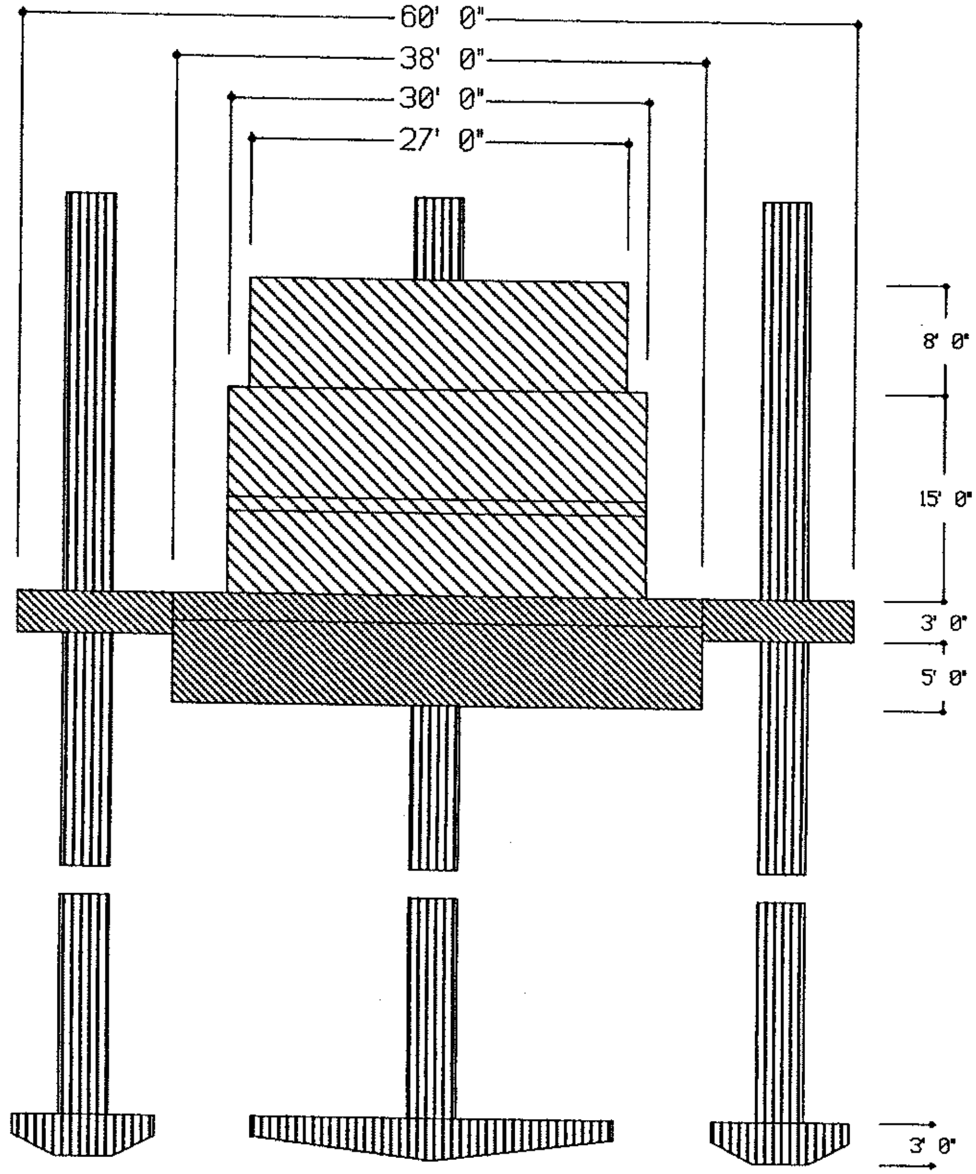
October 31, 1989

FIGURE 1



Total leg length 130 feet

GENERIC LIFTBOAT - SIDE ELEVATION	
STEWART TECHNOLOGY ASSOCIATES	
October 31, 1989	FIGURE 2

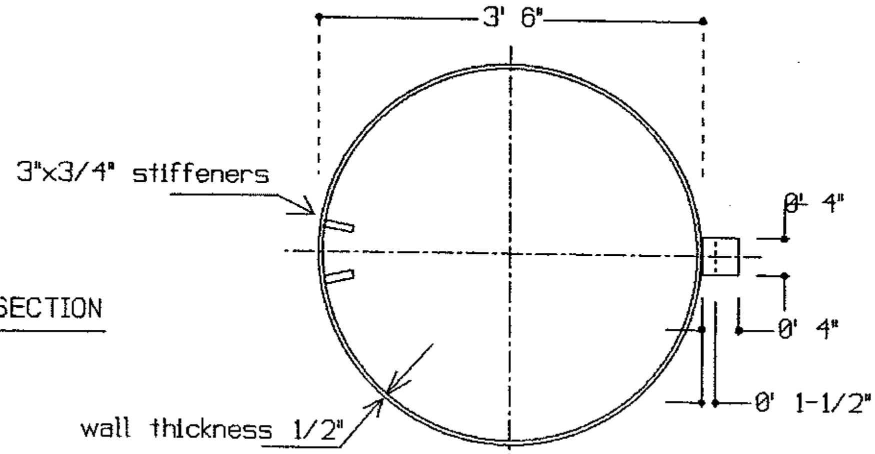


GENERIC LIFTBOAT - BOW ELEVATION

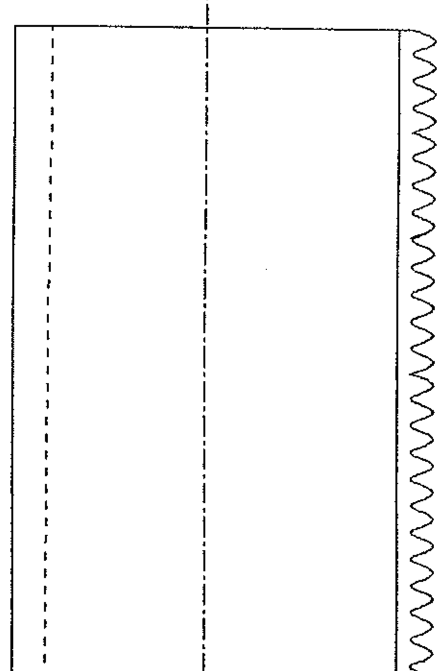
STEWART TECHNOLOGY ASSOCIATES

October 31, 1989

FIGURE 3



TYPICAL SECTION



ELEVATION
SHOWING RACK

NOTES:
1. Steel is 50 ksi yield strength.
2. All legs have racks facing inboard.
3. Rack and stiffeners uniform throughout.

GENERIC LIFTBOAT LEG DETAIL	
STEWART TECHNOLOGY ASSOCIATES	
October 31, 1989	FIGURE 4

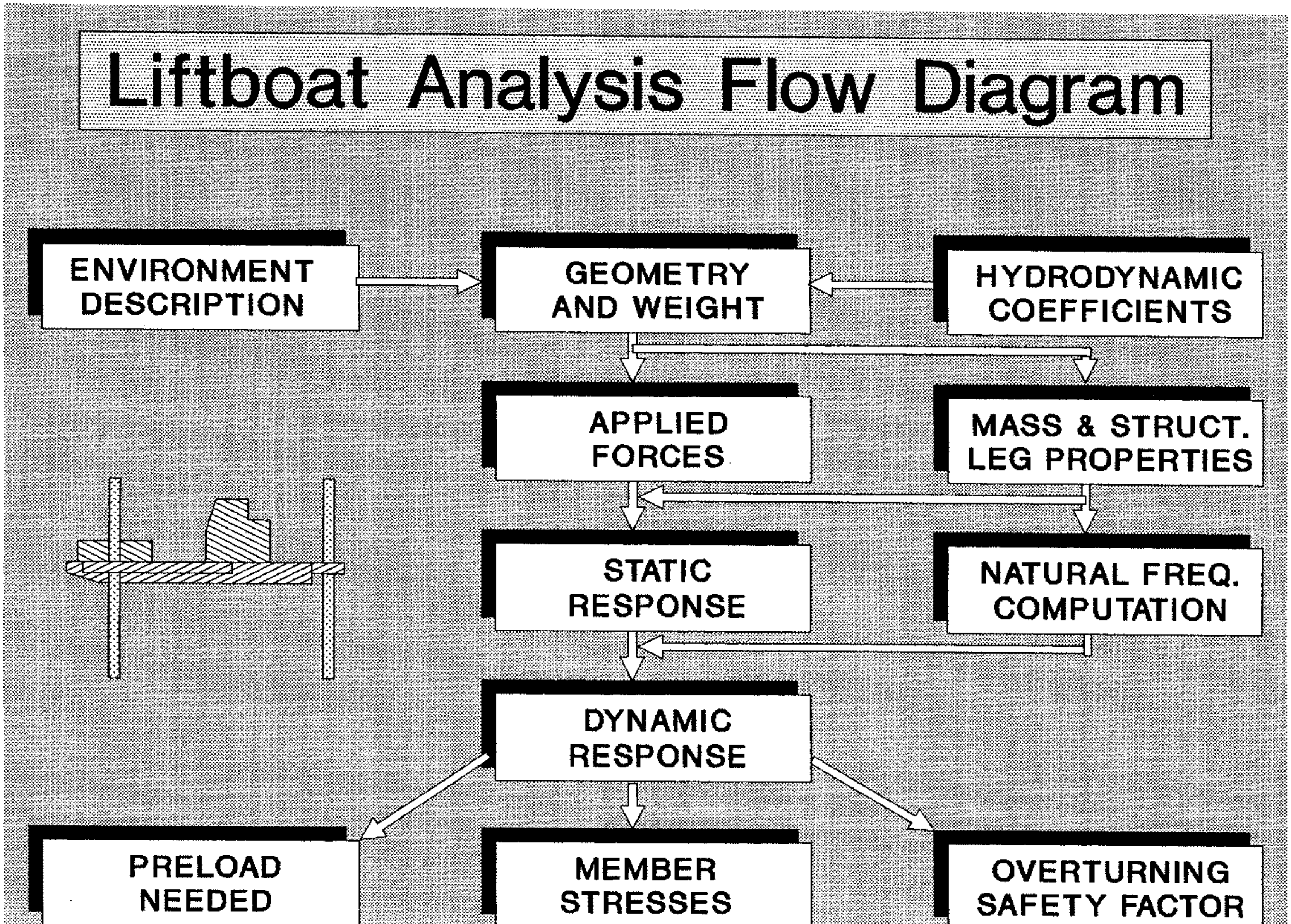
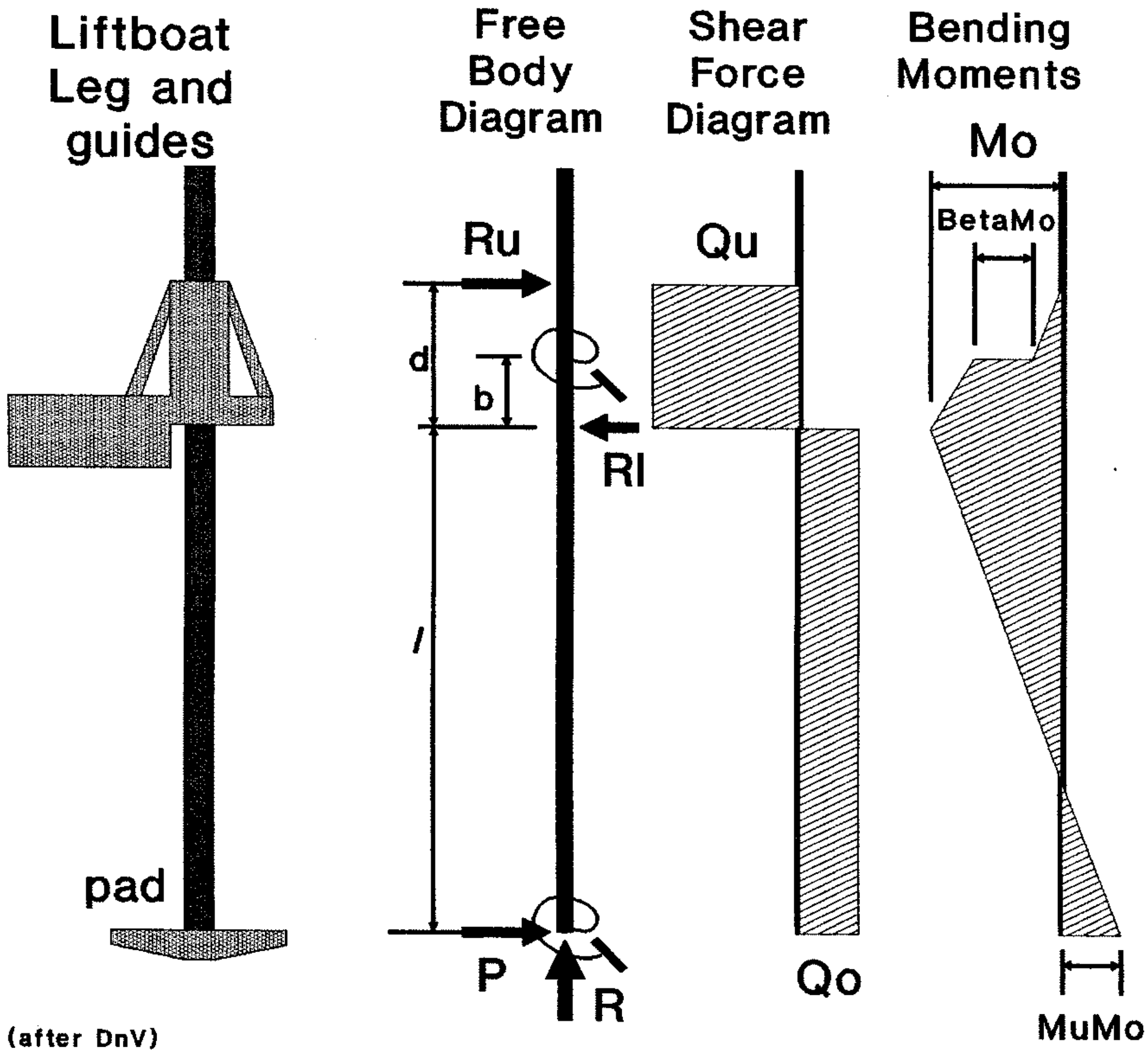

Liftboat Analysis Flow Diagram
ENVIRONMENT DESCRIPTION
GEOMETRY AND WEIGHT
HYDRODYNAMIC COEFFICIENTS
APPLIED FORCES
MASS & STRUCT. LEG PROPERTIES
STATIC RESPONSE
NATURAL FREQ. COMPUTATION
DYNAMIC RESPONSE
PRELOAD NEEDED
MEMBER STRESSES
OVERTURNING SAFETY FACTOR

FIGURE 5

LIFTBOAT LEG FORCE/MOMENT DIAGRAM



$$Ru = \frac{1-Beta}{1-Mu}\,\frac{Mo}{d}$$

$$Rl = Ru + P$$

$$Mo = \frac{P\,l}{1+Mu}$$

$$Qo = P$$

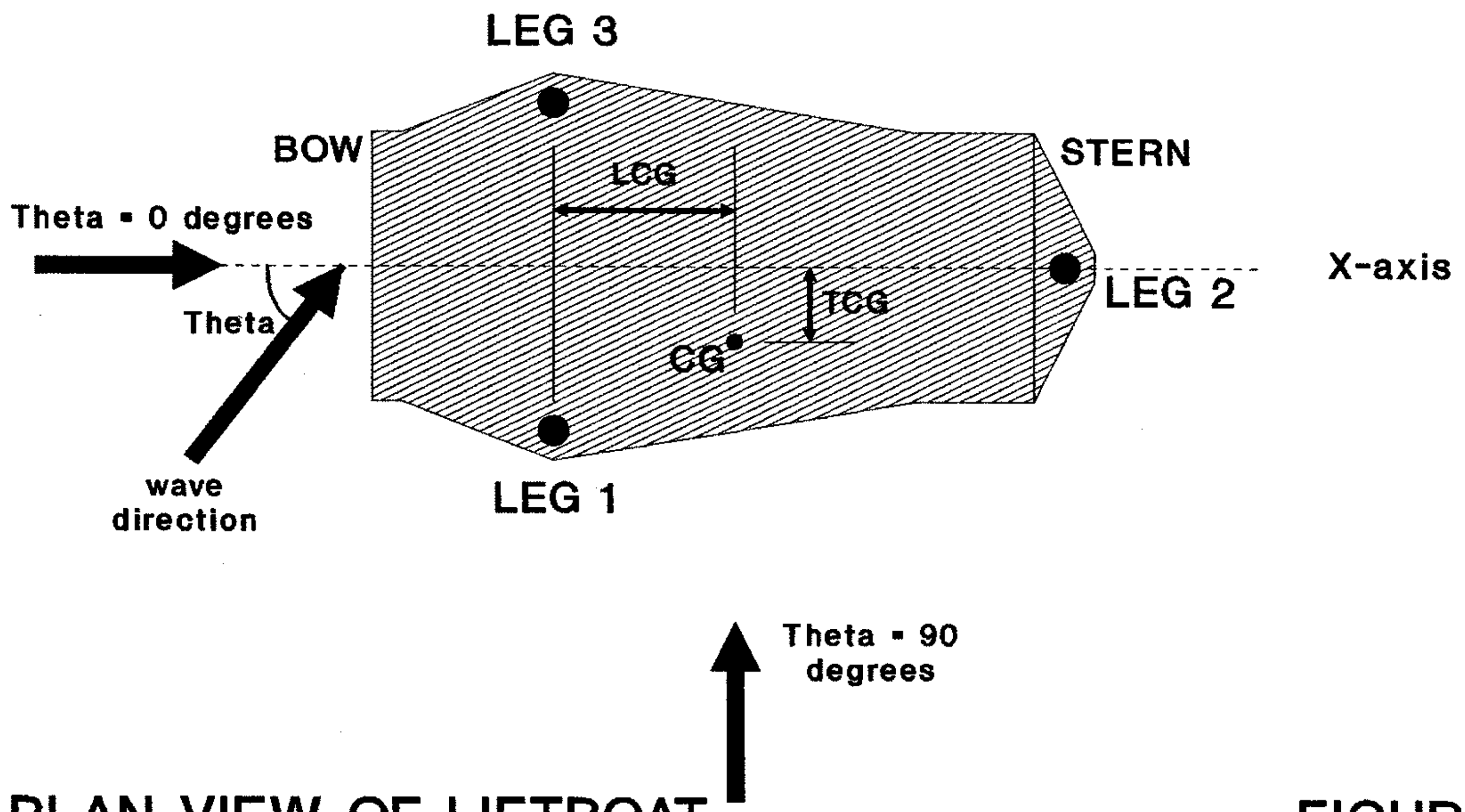
$$Qu = Ru$$

(after DnV)

FIGURE 6

SIGN CONVENTION FOR WAVE DIRECTION

Waves on the port side come from 90 degrees
Waves on the bow come from 0 degrees
Waves on the stern come from 180 degrees



PLAN VIEW OF LIFTBOAT

FIGURE 7

P-Delta Effect

R1 = W/2 - W.delta/a - P.L/a
R2 = W/2 + W.delta/a + P.L/a

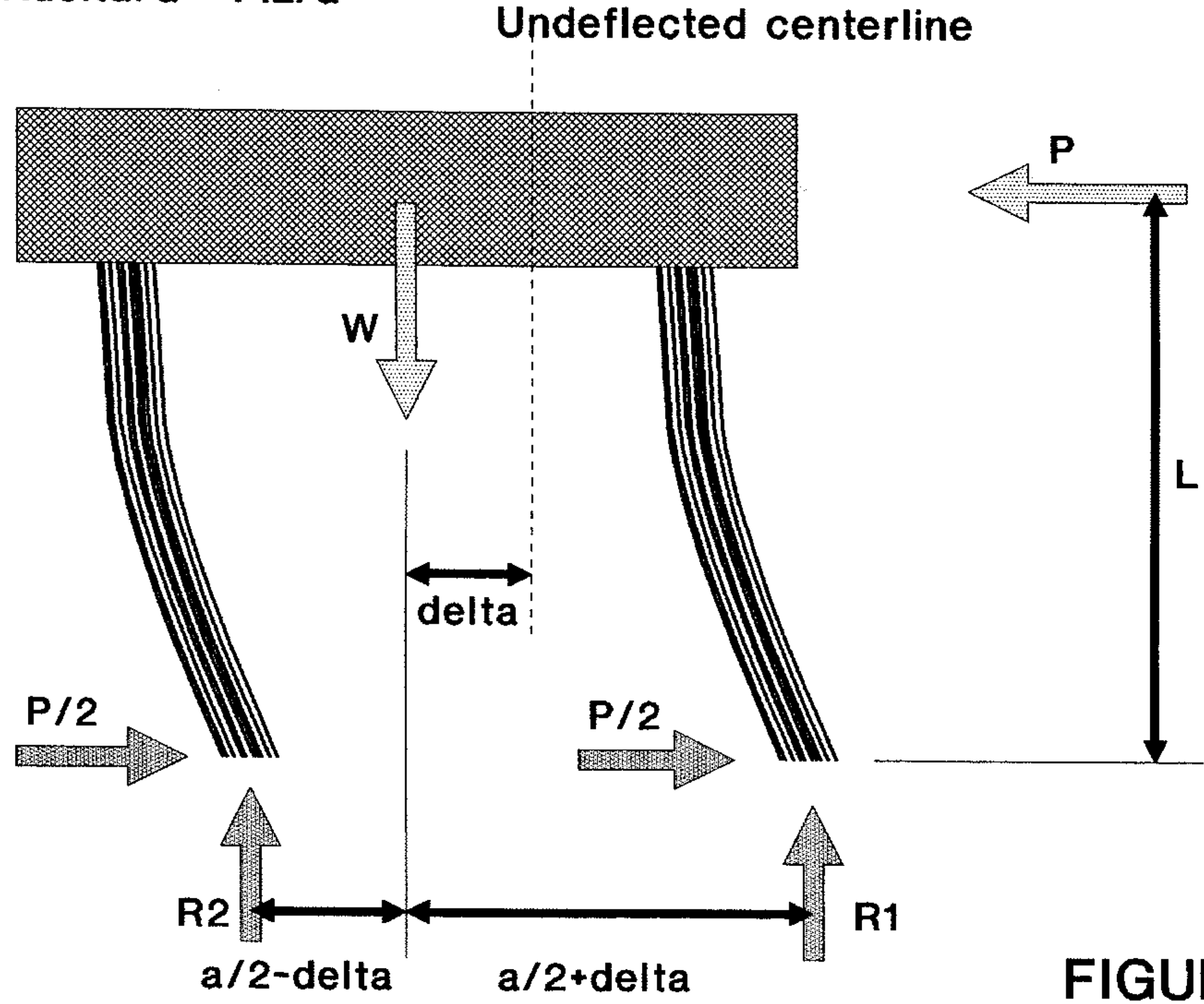


FIGURE 8

LIFTBOAT WINDLOADING

VARIATION OF HULL WIND AREA

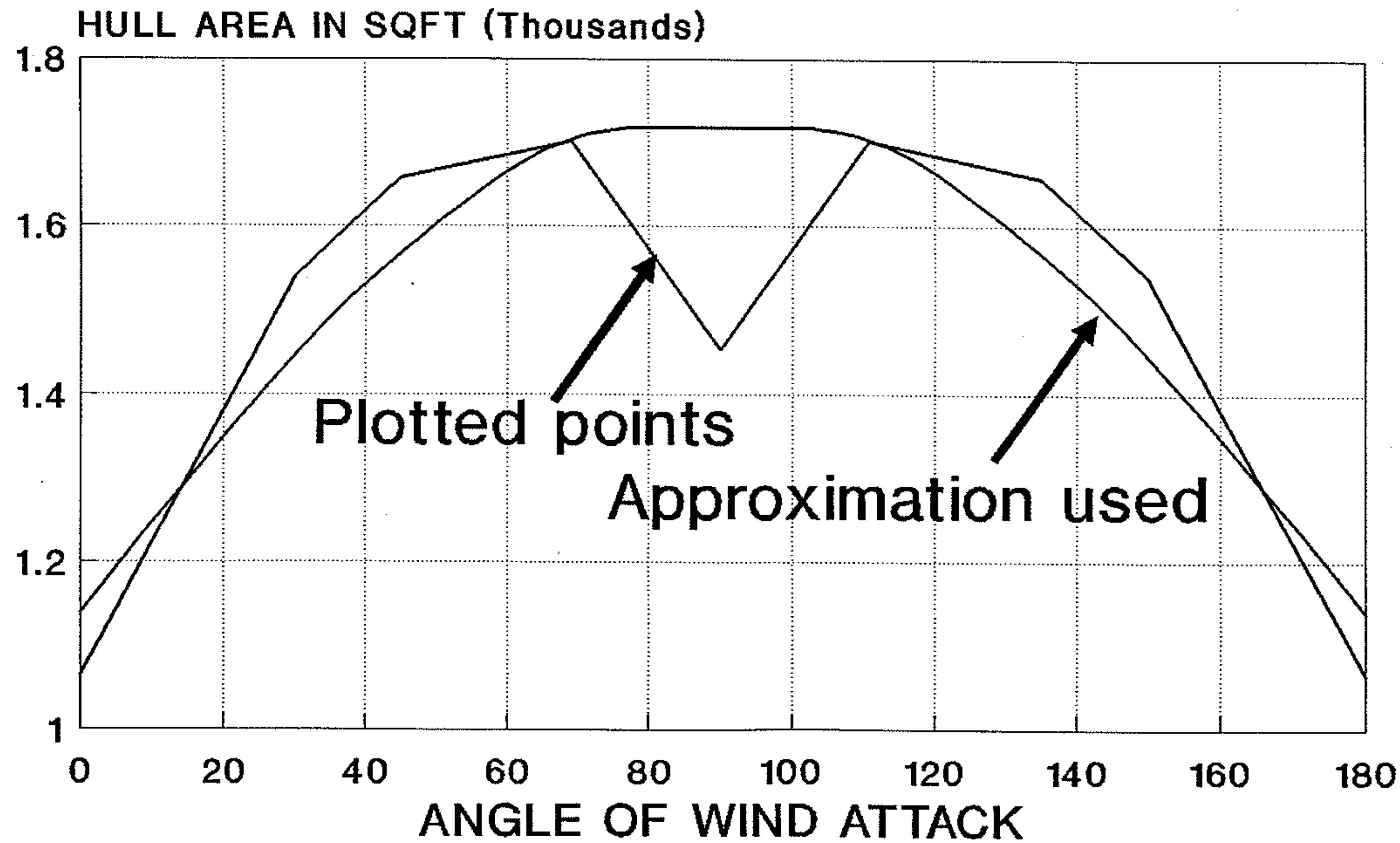


FIGURE 9

LIFTBOAT WINDLOADING
TORSIONAL LEVER ARM VARIATION

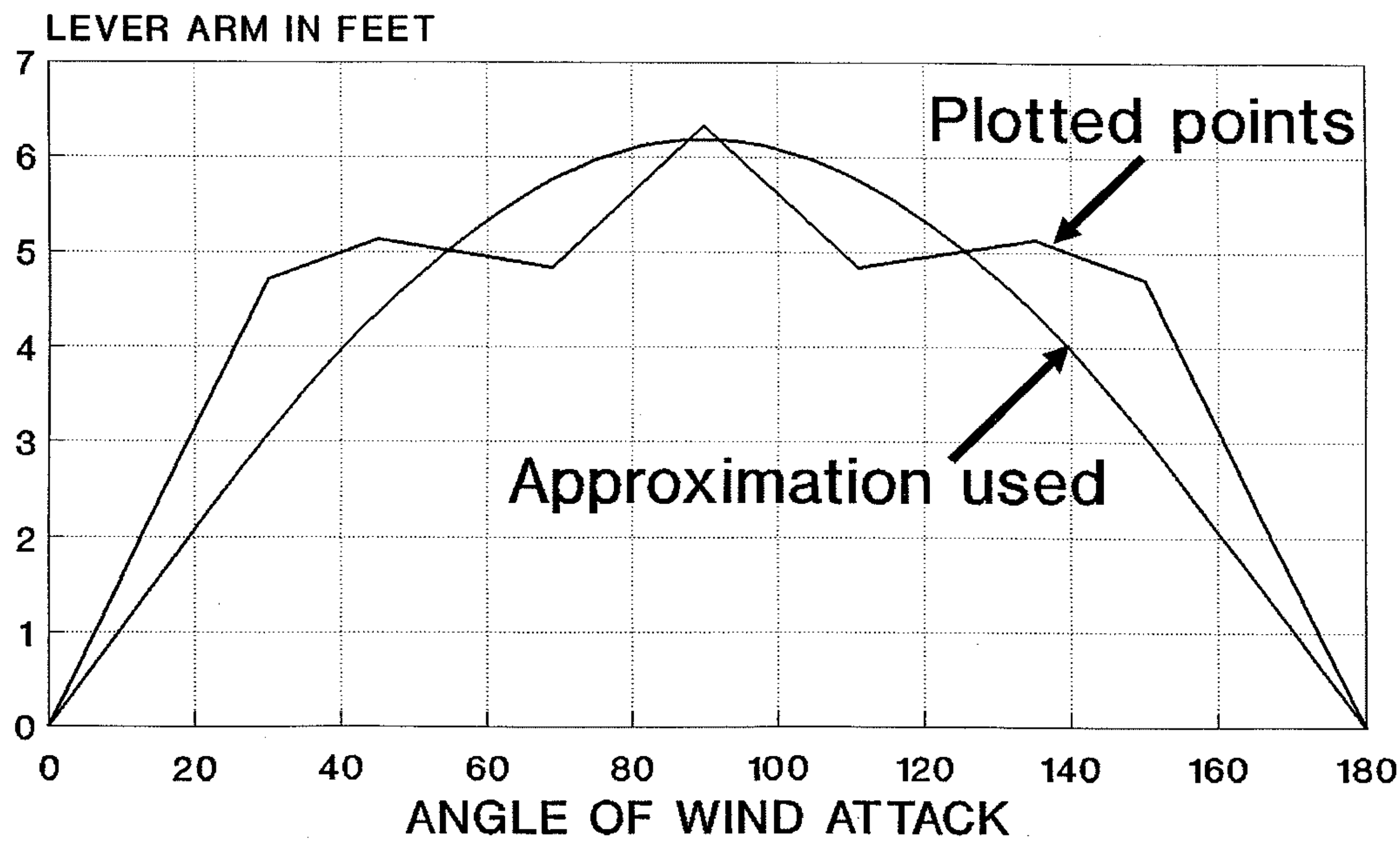


FIGURE 10

LIFTBOAT WINDLOADING
VARIATION OF VERTICAL WIND LOAD CENTER

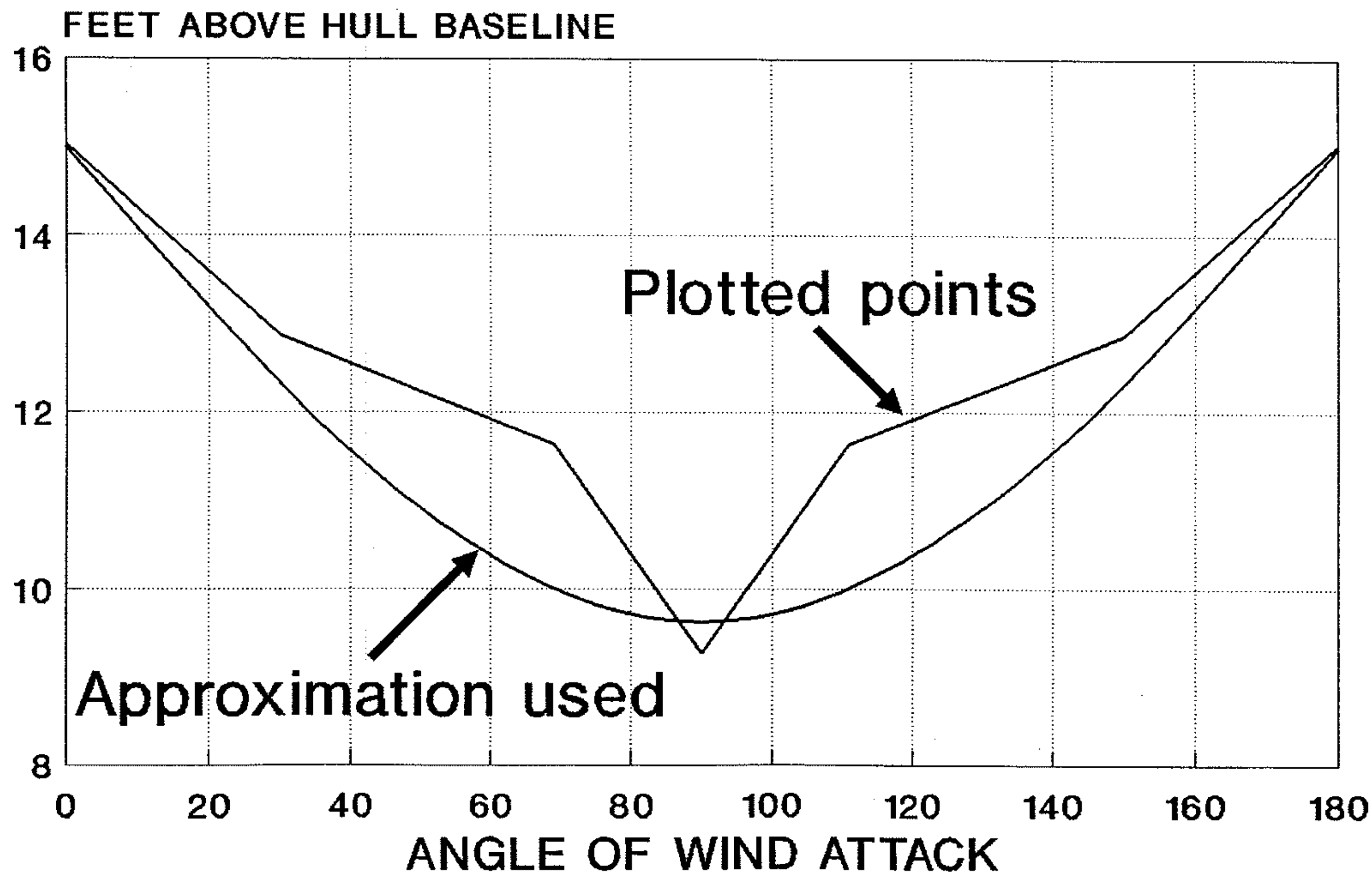


FIGURE 11