R/V Western Flyer Hull-Strength Upgrade

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ABSTRACT

The Monterey Bay Aquarium Research Institute (MBARI) owns and operates the SWATH oceanographic research vessel R/V Western Flyer. *This vessel is of aluminum construction and was designed and built (as reported in Ref. 1) to handle MBARI's remotely operated vehicle (ROV)* Tiburon *in the eastern Pacific.* Western Flyer *was delivered in 1996 and shortly thereafter experienced significant cracking when exposed to relatively moderate seas. This paper outlines the steps that were taken to assess the causes of the cracks and the process used to determine the necessary modifications. The vessel was redelivered in the summer of 1999 and has returned to scientific missions.*

VESSEL DESCRIPTION

MBARI was founded in 1987 with a mission "to achieve and maintain a position as a world center for advanced research and education in ocean science and technology, through the development of better instruments, systems and methods for scientific research in the deep waters of the ocean." MBARI is located in Moss Landing, California, which gives its vessels immediate access to Monterey Bay, one of the most biologically diverse bodies of water in the world with underlying submarine canyons up to 4000 meters deep.

R/V Western Flyer was constructed and optimized to support operation of MBARI's ROV *Tiburon*. Principal dimensions and characteristics before modification are shown in Table 1 and profiles and arrangements are shown in Figures 1 and 2.

The vessel is intended to operate through Sea State 5. She has a Certificate of Inspection (COI) and load line but is not classed by any regulatory agency.

Vessel operations typically consist of one-day voyages and near-coastal voyages averaging three days in length. Extended voyages of two to three weeks' duration are planned, and it is intended to temporarily redeploy her on occasion to a new homeport.

Table 1 – Vessel Characteristics

Displacement at DWL	419 LT
Draft DWL	12 ft.
Length (LOA)	117 ft. 3-5/8 in.
Beam, Molded	53 ft.
Horsepower	2500 HP
Maximum Speed	14.5 knots
Endurance, @ 8 knots	4000 NM
Complement	25 (9 crew plus 16 scientific)

The aluminum structure is 5086 (except for some bulkhead and deckhouse framing, which is 6061). Web frame spacing in the main hull was typically 3 feet with watertight transverse bulkheads spaced 15 feet apart. Figure 3 is a typical structural web frame.

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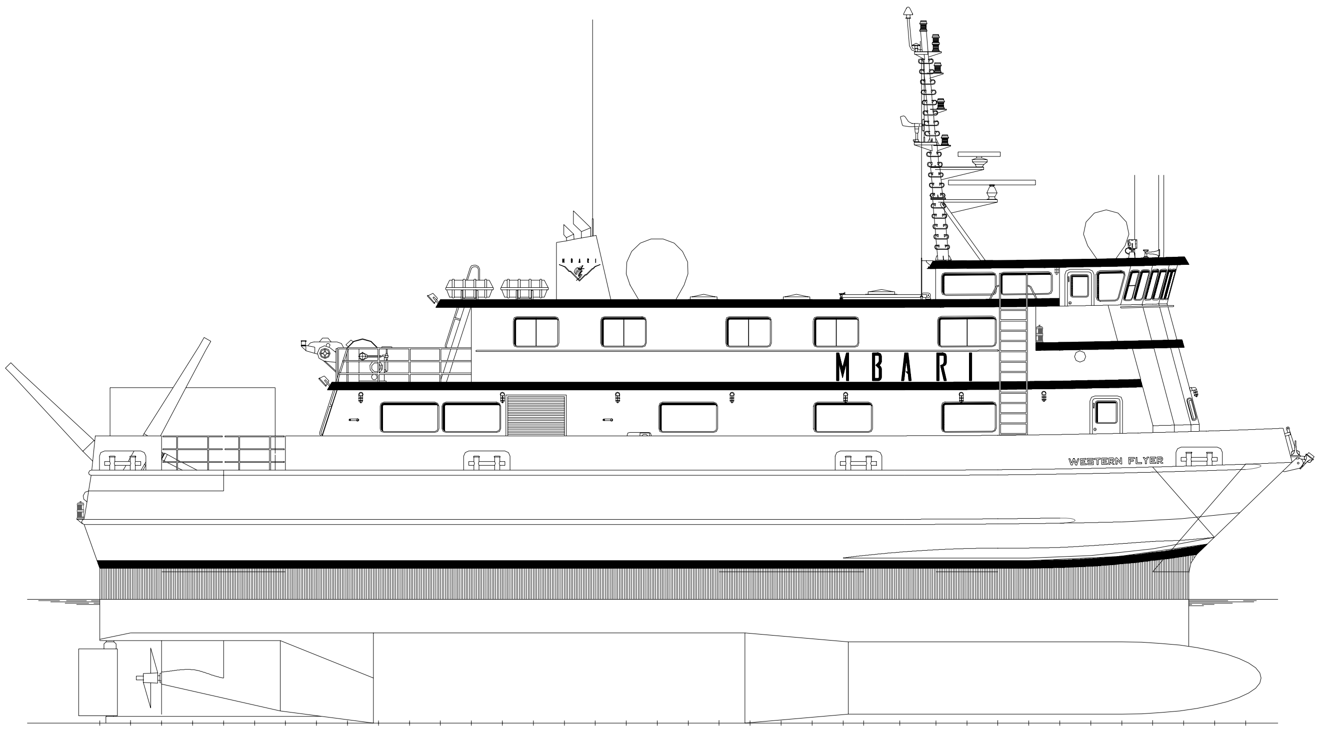

Figure 1. ***R/V Western Flyer*** **– Profile**

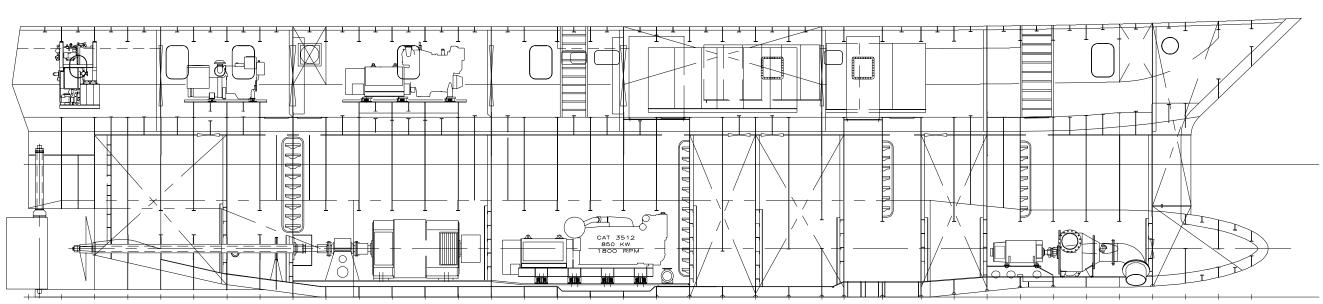

Figure 2. ***R/V Western Flyer*** **- Arrangements**

INITIAL INSPECTION AND ASSESSMENT

Scientific missions for *R/V Western Flyer* began in late 1996. During one of the early missions, cracking appeared in various locations. Initially cracks in the transom were observed when waves slapping against the transom resulted in sufficient water weeping through to cause the bilge alarm in the steering flat to go off. The crew subsequently initiated a structural search that resulted in the identification of additional cracks in the vessel's structure. The crew estimated that the sea state was 3 to 4, with the most significant seas coming from the starboard beam.

After the vessel returned to port, The Glosten Associates were retained to do an inspection and provide an assessment. The initial detailed inspection, made with the crew, resulted in identifying cracks that could be lumped into three main categories:

Web Frame Cracks. Typical web frames on *R/V Western Flyer* have brackets on each side in way of the haunch girder notch radius. The majority of the web frames with this type of detail exhibited no cracks or visible failures. Cracks were observed where there was a lack of brackets and/or poor local construction details.

Transom Cracks. The transom cracks all started in a hard spot on the inboard side of the vessel at a point where plate butts and seams converged in a corner. The horizontal transom cracks were approximately 20 inches long and located 5 feet above the waterline.

Watertight Bulkhead Cracks. The cracks in the watertight bulkheads were in way of the radius haunch girder notch. Inspection, from a boat, of the exterior of the vessel in way of the bulkheads also revealed vertical shell plate cracks approximately 6 inches long, inboard and outboard, port and starboard, in way of the haunch notch radius.

No known finite element analysis had been performed on the vessel, and the immediate solution was to repair the cracks and monitor the structure. Because of the uncertainty that these fixes would succeed, the intent was to expose the vessel to progressively worsening sea states in the immediate area. Then, if new cracks started to develop or the seas became excessive, the captain would alter course to minimize the loads. MBARI also initiated a rigorous inspection routine of the structure while the vessel was at sea.

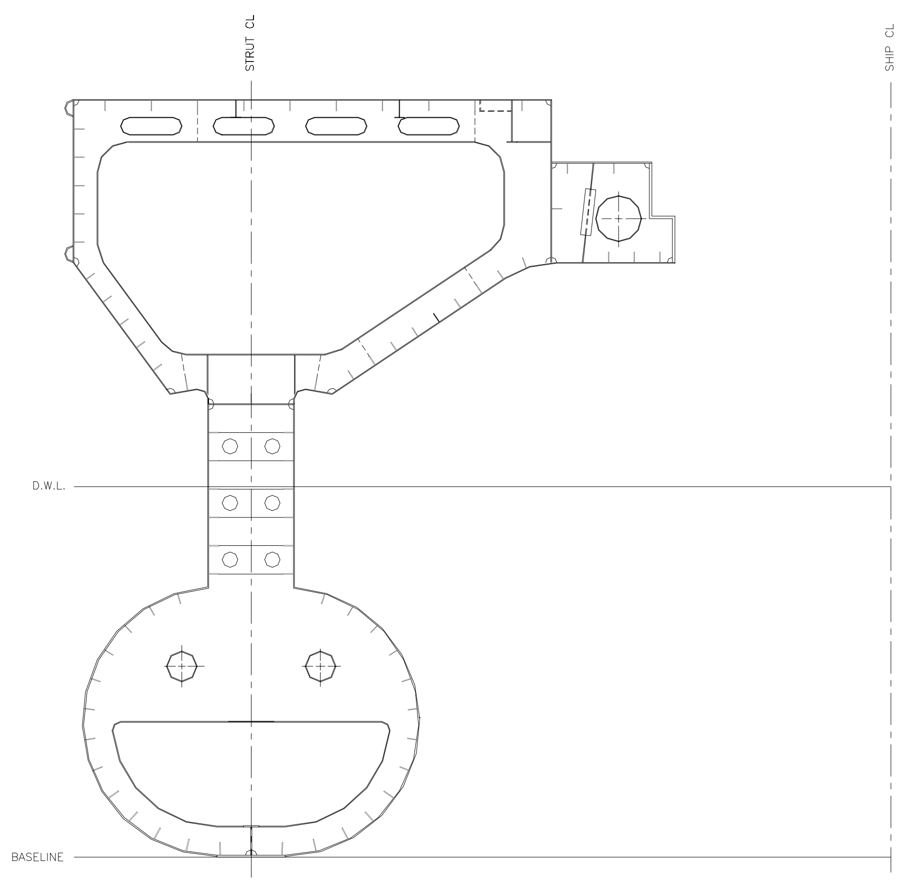

Figure 3. *R/V Western Flyer* – Typical Web Frame

INITIAL FINITE ELEMENT ANALYSIS

Two-dimensional models were made of a typical bulkhead and web frame. The models were developed and analyzed using the commercial FEA package COSMOS/M.

Determining the loading on the vessel required: climatology selection, computation of fluid forces on the individual hulls for a range of incident wave frequencies, integration of these force transfer functions over the wave spectrum, estimation of extreme loads in each mode and, finally, obtaining a set of load cases that could then be applied to the structural model.

Three different climatologies corresponding to Sea States 3, 4, and 5 were investigated. Only beam seas were considered for this initial assessment. The loads on the vessel for regular incident waves ranging in frequencies from 0.389 radians/second (period 16 seconds) to 1.94 radians/second (period 3.2 seconds) were determined using a program called WAMIT (Wave Analysis MIT). The total fluid pressure was integrated over the submerged surface of each hull to obtain the forces and moments acting on the hulls.

Once the force spectra in regular waves were determined, they were appropriately integrated over a unidirectional Bretschneider spectrum to obtain the corresponding extreme loads acting on each hull in a given sea condition. The short form statistical extreme force was calculated in accordance with Ochi [Ref. 4], assuming a 10% probability of being exceeded in a run of 1,000 loading cycles, which roughly corresponds to a 2 to 2.5 hour storm duration.

The extreme forces and moments in the various modes do not occur at the same instant; therefore, in addition to individual extremes, a set of load combinations were determined to facilitate structural analysis. Each load combination included the extreme value for one selected mode and the most probable joint values for the other modes conditioned on the fact that the selected mode is maximized. The extreme value occurred when the transverse force is maximized.

The maximal load was then allocated to the bulkhead and web frame models based upon the number of bulkheads and web frames and their relative stiffness, as calculated in the finite element models. The models were run with and without the brackets in way of the haunch girder notch (added as part of the repairs). Even though there was a significant stress reduction realized around the brackets (approximately 25% locally), the stress in way of the haunch radius in Sea State 5 was 42 ksi. Haunch radius stresses were localized but the analysis also identified areas of potentially high stress in the door cutout.

This method of developing loads for a 2D model slightly overpredicted the stresses when compared with the 3D model. The maximum stress from the 2D model was 42 ksi. However, this stress is localized at the edge of the bulkhead plate. The area just above the haunch radius shows stress of 28 ksi. This same location in the 3D model shows stress of 26 ksi.

DETERMINATION OF OPERATING CONDITIONS TO MINIMIZE STRUCTURAL LOADING

Based upon the initial structural analysis, MBARI expanded the analysis effort to include an estimate of operating conditions that would minimize vessel loading and allow the vessel to continue to operate until a global structural analysis and long term remedy was determined and implemented. Results of the initial finite element analysis work provided a basis for estimating a maximum acceptable value for the side force and moment based upon the sea state.

Using the WAMIT computer program, forces were computed at vessel headings from bow quartering seas, to beam seas, to stern quartering seas. The forces were then analyzed over a range of Bretschneider random sea state spectrums to determine total forces and moments applied to the vessel in a given sea condition.

Results plotted in the form of limiting significant wave height versus relative vessel heading were developed. The simplest presentation of data, with the most conservative operating conditions, is shown on Figure 4.

RESTRICTED VESSEL OPERATIONS

Based upon the initial results, MBARI initiated and maintained a program of rigorous structural inspection and vessel operating limitations. By the end of June 1997, after approximately two months of limited operations, *R/V Western Flyer* had experienced 111 new cracks. The vast majority of these were at the start or finish point of welds in the haunch area. Cracks were typically 1/8 inch to 1/2 inch long. No new cracking was observed in any base metal.

As a result of the numerous new cracks, a stress monitoring system was installed in the vessel in the late summer of 1997. The stress monitoring system had a real-time audio and visual alarm in the pilothouse so that a less severe heading resulting in reduced structural loading could be undertaken when a preset stress limit was reached.

The stress monitoring system, structural inspection regimen and guidance provided by the heading versus sea state plots remained in place until the vessel entered the shipyard in the spring of 1998.

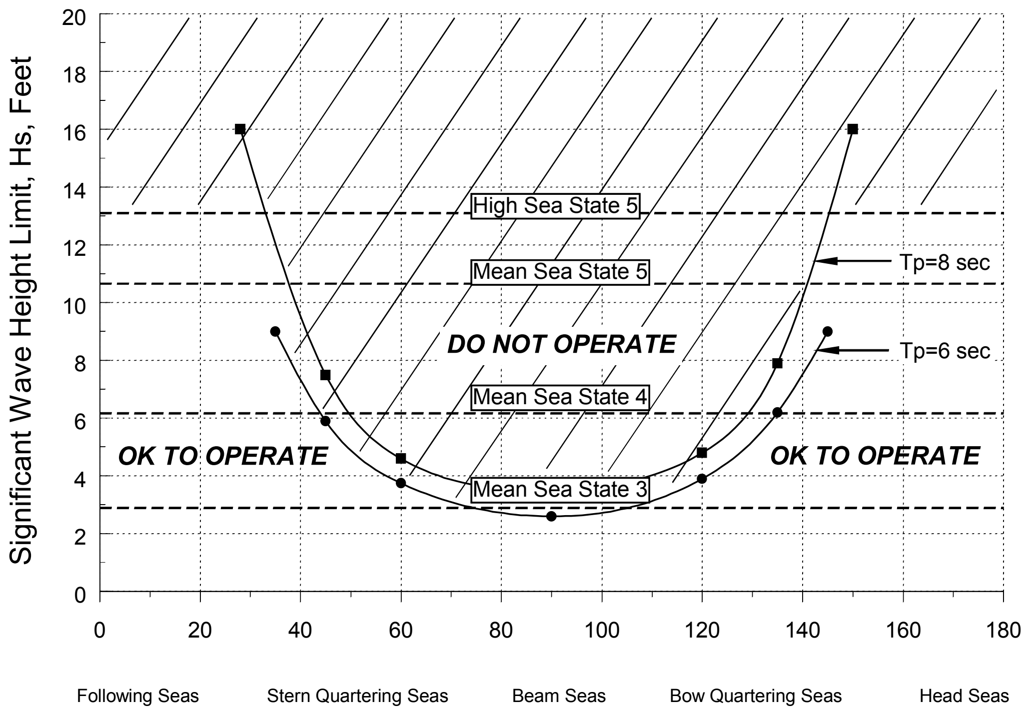

Figure 4. Operating Conditions in Various Wave Heights and Vessel Headings

3-D MODEL

Upon completion of the initial structural analysis and development of the operational limitations based upon the heading and seaway, a three-dimensional finite element model was begun. This effort was divided into two phases. The first phase was an analysis of the existing vessel structure to determine if there were other areas where the structure was deficient. The second phase was to determine the modifications necessary to allow the vessel to operate without limitations on heading in the intended environment.

First, we reviewed and confirmed the goals, design constraints and process that would be used in the analysis. Broadly summarized, they are as follows and were determined after several meetings with the ship's crew and operators:

- Year-round operations in Monterey Bay and summer operation on the Juan de Fuca ridge
- Sea State 5 operations
- Maintaining seakeeping performances
- Minimizing any increase in weight
- Admeasurement tonnage less than 500 gross tons
- Estimated fatigue life of 20 years based upon operations in Monterey Bay
- ABS Peer Review

We developed a global 3D full vessel finite element model including the deckhouse, as shown in Figure 5. The main structural components of the hull were modeled utilizing several different element types as follows:

- Stiffened plate panels – orthotropic quadrilateral shell element (QUAD4).
- Web frames – hybrid beam element located at the neutral axis. This element uses an effective plate breadth to determine the flexural properties, but disregards the plating for axial stiffness because the in-plane stiffness of the plating is accounted for in the panel element.
- Lower hull bulkheads – super element consisting of in-plane membrane elements.
- Strut and haunch bulkheads – orthotropic quadrilateral shell element (QUAD4).
- Miscellaneous – triangular constant strain element.

Table 2 lists the material properties of the aluminum alloys used in the construction and modifications. Most of the existing structure consists of 5086H32 aluminum alloy. Only the extruded bulkhead stiffeners and superstructure framing use the 6061-T6 alloy. New plating and built-up members in the modified vessel were 5083-H321 aluminum, which allowed a higher stress level and accordingly minimized weight growth.

The strength of 5000 and 6000 series aluminum alloy is reduced at higher temperatures and behaves like annealed metal when heated to the high temperatures that occur during welding. The differing yield strengths are considered in the analysis of the results based on the location of stress concentrations relative to welds.

For the analyses, safety factors were based upon the Det Norske Veritas High Speed Aluminum Vessel Rules [Ref. 3].

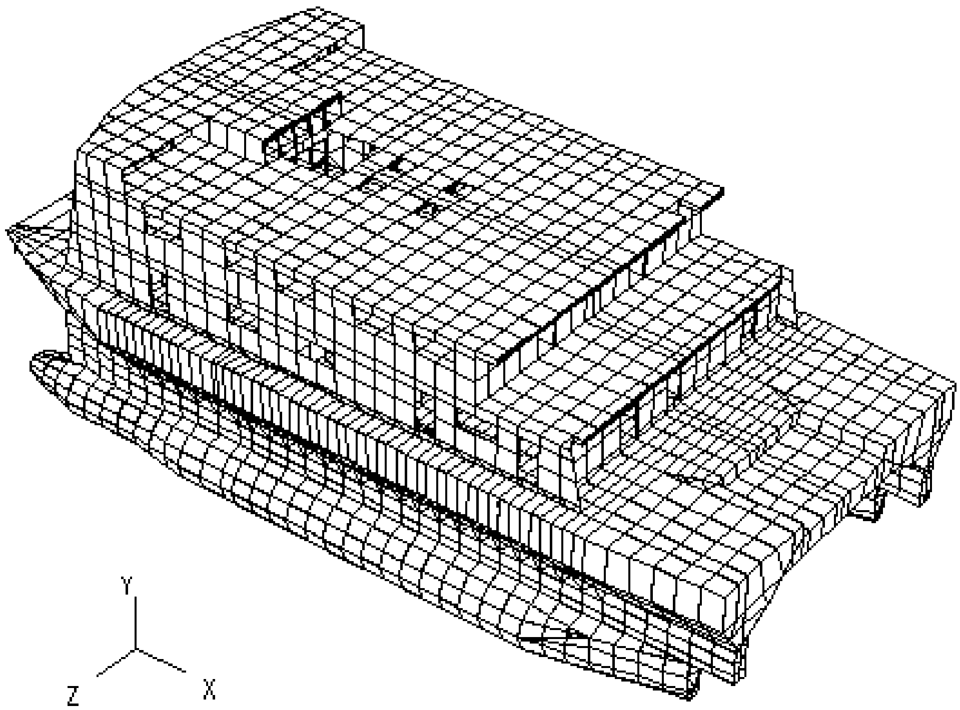

Figure 5. ***R/V Western Flyer*** **– Finite Element Model**

Table 2 – Aluminum Material Properties			
Aluminum Alloy	5086-H32	5083-H321	6061-T6
Elastic Modulus, psi	1.020E7	1.020E7	1.020E7
Poisson's Ratio	0.30	0.30	0.30
Ultimate Strength, psi	35,000	40,000	35,000
Yield Strength, psi	28,000	31,000	35,000
Weld Zone Yield Strength, psi	14,000	18,000	15,000
Density, lbs/in^3	0.100	0.100	0.100

DETERMINATION OF DYNAMIC LOADS

Maximum load cases in the form of total pressure distributions on the wetted surface of the hull were developed for all six degrees-of-freedom using an equivalent irregular wave (which, with its broader band frequency, is distinguished from the equivalent regular wave developed by the American Bureau of Shipping). The ABS equivalent regular wave definition results in the application of a simple sinusoidal wave. It acts as the vehicle to recast the results of probabilistic analysis to a deterministic format more suitable for finite-element analysis, but does not correspond to any real or extreme condition at sea. In the classical representation of the seaway as the superposition of a number of different waves of different frequencies, the equivalent regular wave fails to provide a mechanism for inclusion of the various harmonic components. In view of this apparent limitation, an equivalent irregular wave was developed. The vehicle used to form the irregular wave is the Fourier-Stieljes integral, which is consistent with the classical representation of the seaway as the superposition of a number of waves of different frequencies. Reference 2 contains further discussion of the development of the equivalent irregular wave pressure distributions.

Figure 6 compares the design load to the lifetime extreme loads for both long crested and short crested seas as a function of service life of the original vessel. The design squeezing/prying moment developed for high Sea State 5 represents a upper bound on the lifetime extreme in long crested seas, assuming compliance with seamanship guidelines in the sailing instructions.

The design load for the modified vessel is approximately 8% higher than the load for the existing hull configuration, largely due to the lower hull pontoon modifications described later. Table 3 compares the extreme loads for the existing and modified vessel.

Table 3 – Comparison of Lifetime Extreme Loads	
Vessel	Prying Design Load [kip-ft] @ DWL
Existing	5952
As-modified	6405

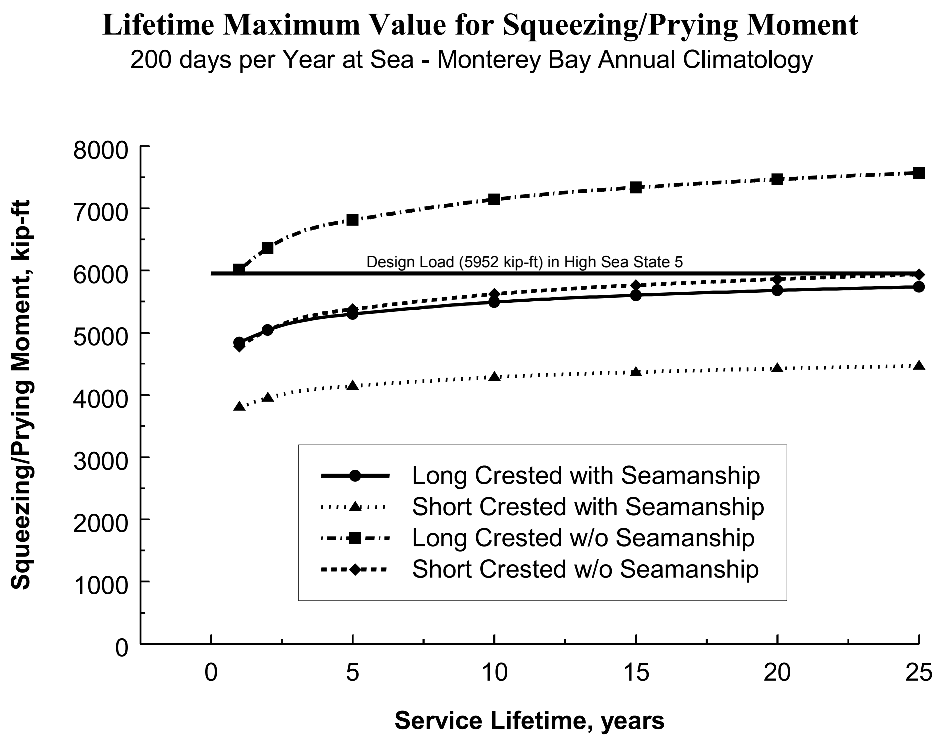

Figure 6. ***R/V Western Flyer*** **– Design Load, Existing Hull**

RESULTS

The analysis of the existing structure when exposed to the Sea State 5 loads showed:

- The cross structure exhibited local panel buckling failures in the transverse web plating aft of the moonpool in the squeezing load condition. (The examination of the vessel's transverse web plating indicated that buckling had occurred.)
- The haunch/strut intersection was highly stressed (where cracking had been experienced).
- The aft intersection of the deckhouse corners with the main deck and bulkhead below show high stress levels (again, where cracking had been experienced).
- Panel buckling throughout the deckhouse.

The area with the highest stresses is the deck where the majority of equipment and systems are located. Approximately 15 different schemes were developed and analyzed to arrive at a suitable solution.

Early in the analysis, two schemes showed promise and were more fully developed than the others:

- Adding new half frames throughout the vessel and strengthening and deepening the existing frames.
- Providing exterior hull blisters.

Regardless of the option selected, due to the weight increase and the need to maintain the operating draft at or near 12 feet, the diameter of the transition section in the lower hull was moved forward approximately six frames (18 feet) providing approximately 30 tons more displacement.

The vessel was model tested at Marineering Ltd., with and without the blister to compare the vessel motion. After review of the results and because of operating concerns about the blisters' interfering with ROV operation, the half frame option was selected.

The next step in the design process was to use the computer models and software to develop structure modifications to allow the vessel to operate in the specified conditions. This effort took about three months, and included the development of drawings for every frame and half frame. Producibility was a key consideration for the structural reinforcements.

A summary of modifications to support the lifetime load are listed below, and stress plots of the before-and-after structure are shown in Figure 7.

The type and extent of modifications that were necessary can be summarized as follows:

1) Fair in the notch at the intersection of the strut and haunch to eliminate the stress concentration (Fig. 8).
2) Add half frames to the haunch area below the main deck, above the tank top, and outboard 11 feet off centerline to strengthen the haunch/strut intersection (Fig. 9).
3) Deepen existing outboard haunch frames to strengthen the haunch/strut intersection (Fig. 10).

4) Add transverse half frames to the cross structure aft of the moonpool between Frames 18 and 32 to prevent buckling of the main deck and wetdeck plating.
5) Add transverse flat bars and stiffeners to the deckhouse to prevent local plate buckling.
6) Replace aft bulkhead of the house with thicker plate of stronger aluminum alloy and add heavy insert plates at the aft house corners to support high load in this area.
7) Modify the deckhouse to support ABS design deck loads. Add longitudinal girders and stanchions to the deckhouse as necessary to break long transverse spans.
8) Add vertical flat bar stiffeners to transverse web plating in the cross structure aft of the moonpool to prevent further local panel buckling failures.
9) Increase locally the diameter of the pontoon and extended it approximately 18 feet, to compensate for the additional weight (Fig. 11).

VESSEL MODIFICATION

As noted earlier, the vessel had been modified at Bay Ship and Yacht in Alameda, California. Several design issues were raised and resolved during this modification effort, the most interesting of which include the notch modifications, the lifting and blocking of the *Western Flyer*, and the expansion of her capabilities.

Notch

One of the primary construction concerns was the notch, the area where the haunch plate meets the sides of the strut. The original design had a spray-rail-like structure that led to stress concentrations. To remove these stress concentrations, the spray rail concept had to be discarded, and the haunch shell plate extended down to the strut sides (Fig. 8). This modification reduced the stresses in the frames to an acceptable level; however, the intersection of the new fairing plate and the strut side became an area of concern. A method of construction was required that kept to a minimum the amount of weld at the intersection of the haunch and strut.

The initial concept for the notch replacement shape was to construct the new pieces as continuous modules approximately 20 feet long. The modules were to contain the shell plate, a flanged plate, internal framing and an external collar plate. The yard discarded this concept because the vessel contained irregularities that would make difficult the alignment of a prefabricated module with the existing structure.

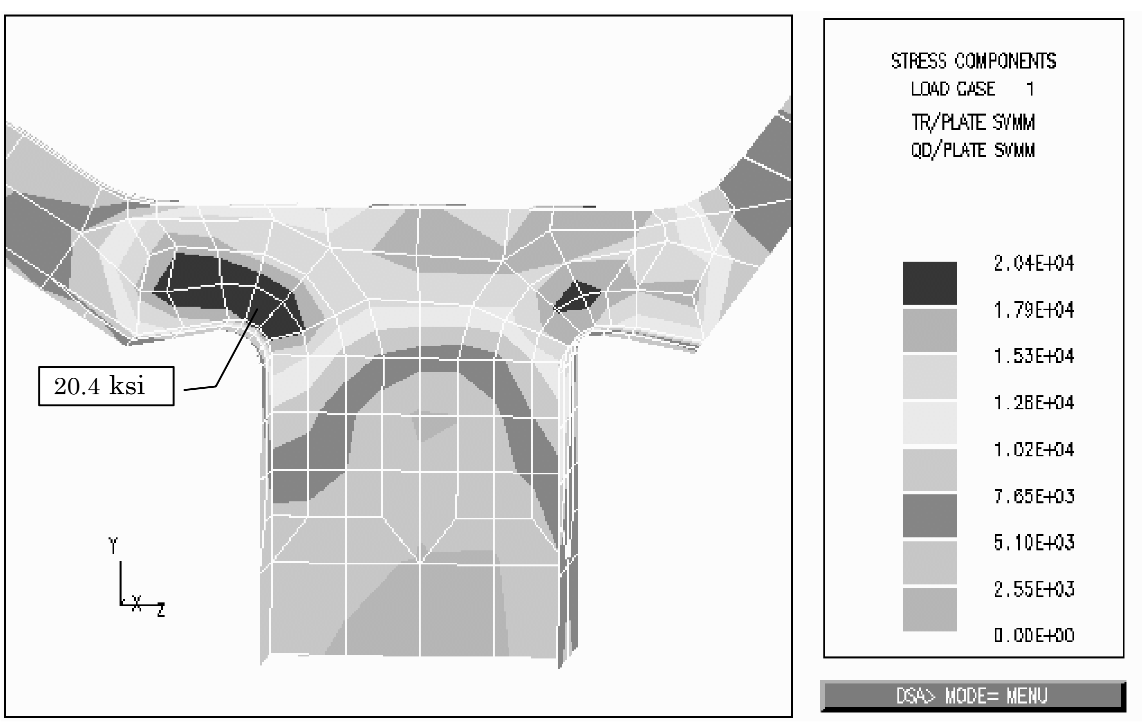

Figure 7a. ***R/V Western Flyer*** **– Frame 27, Von Mises Stress - Modified**

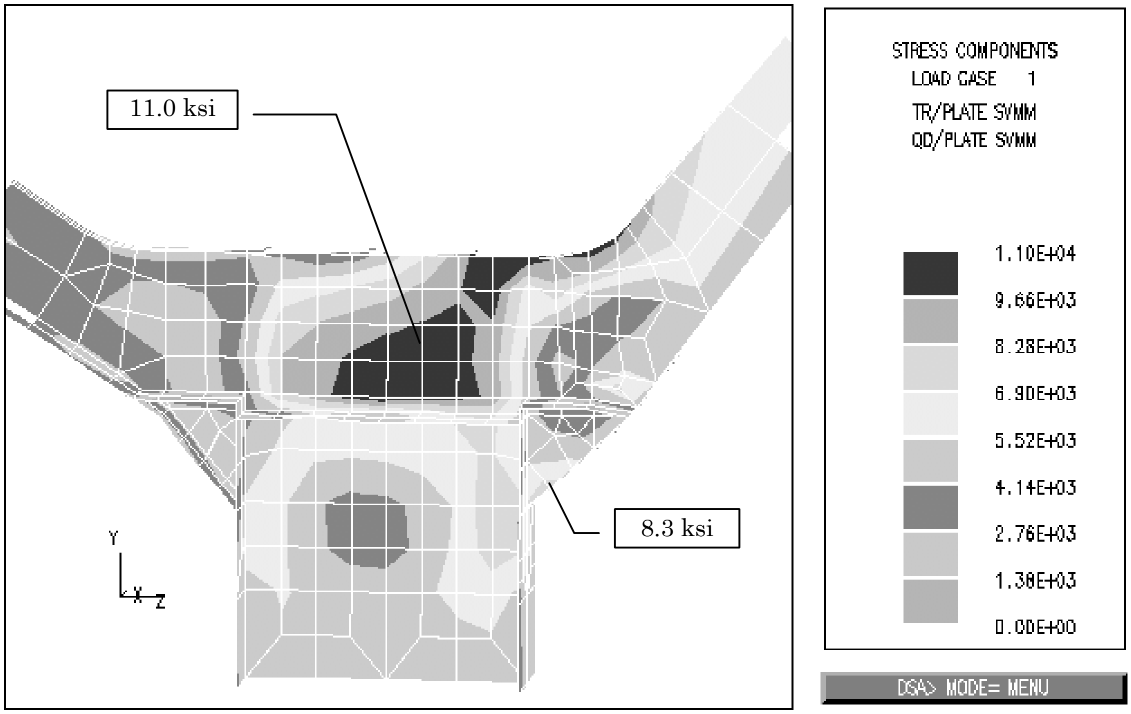

Figure 7b. ***R/V Western Flyer*** **– Frame 27, Von Mises Stress – Before Modification**

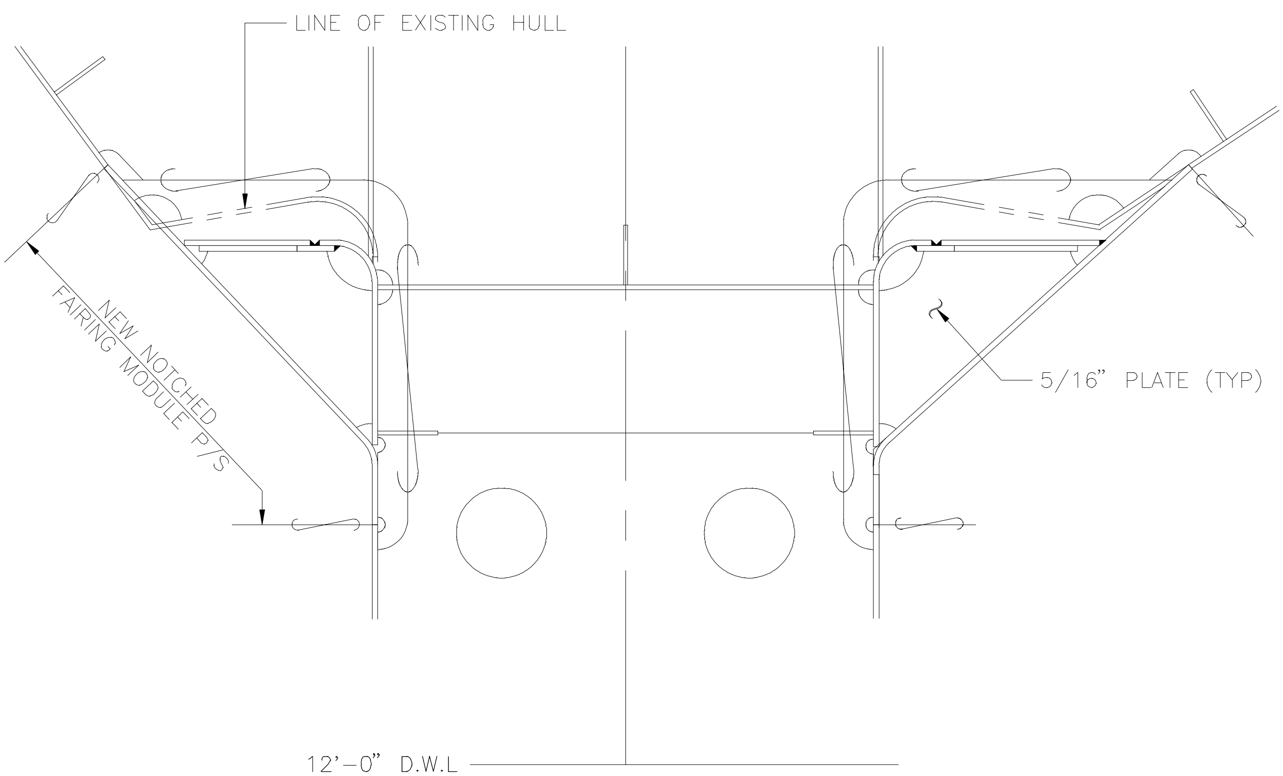

Figure 8. ***R/V Western Flyer*** **– Notch Fairing**

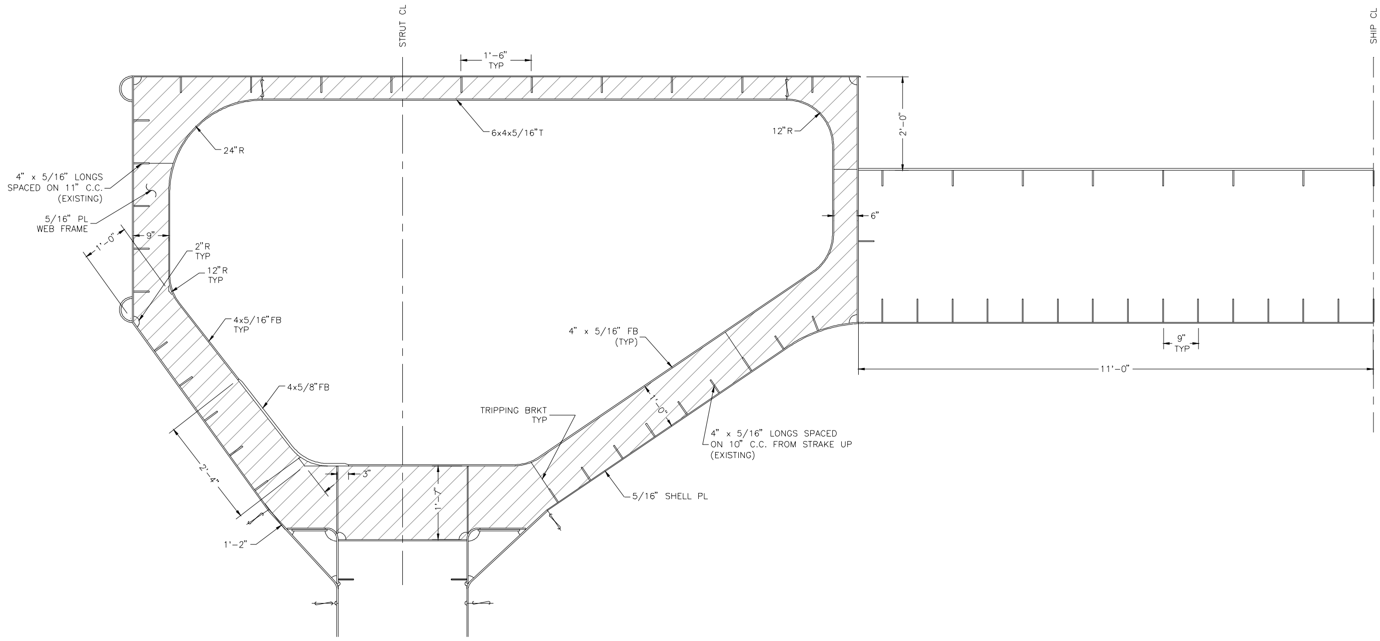

Figure 9. ***R/V Western Flyer*** **– Typical Half Frame**

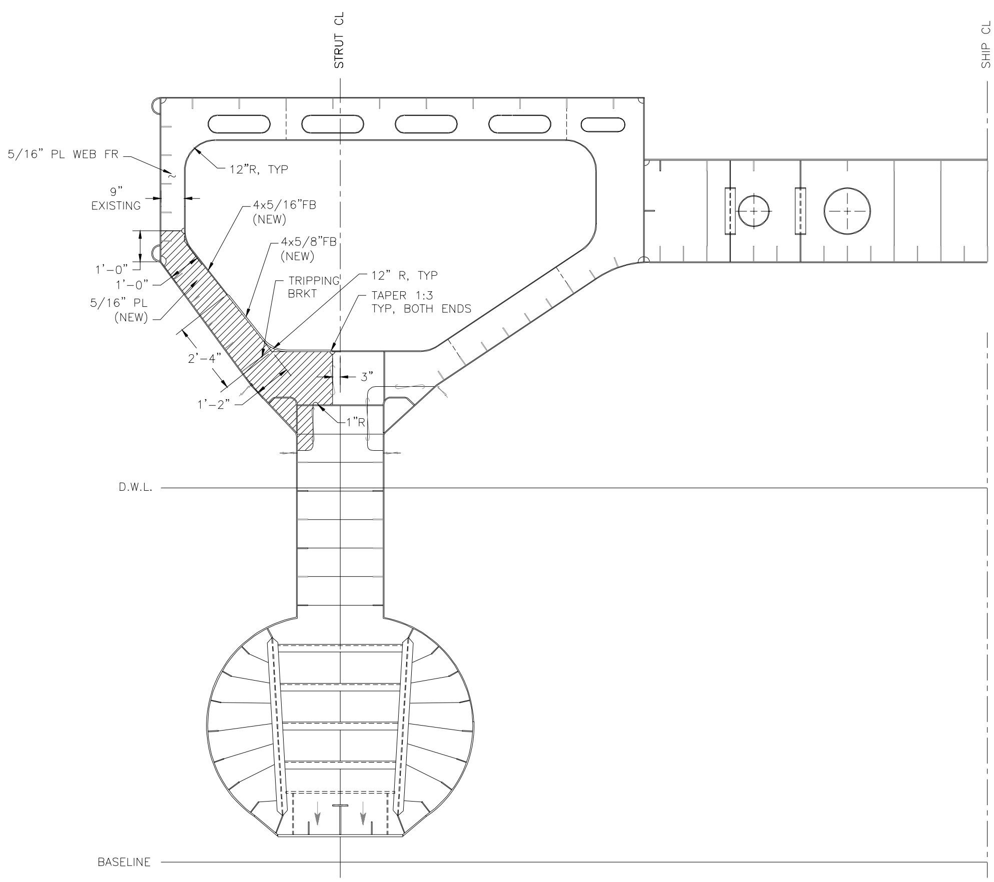

Figure 10. ***R/V Western Flyer*** **– Typical Frame Modification**

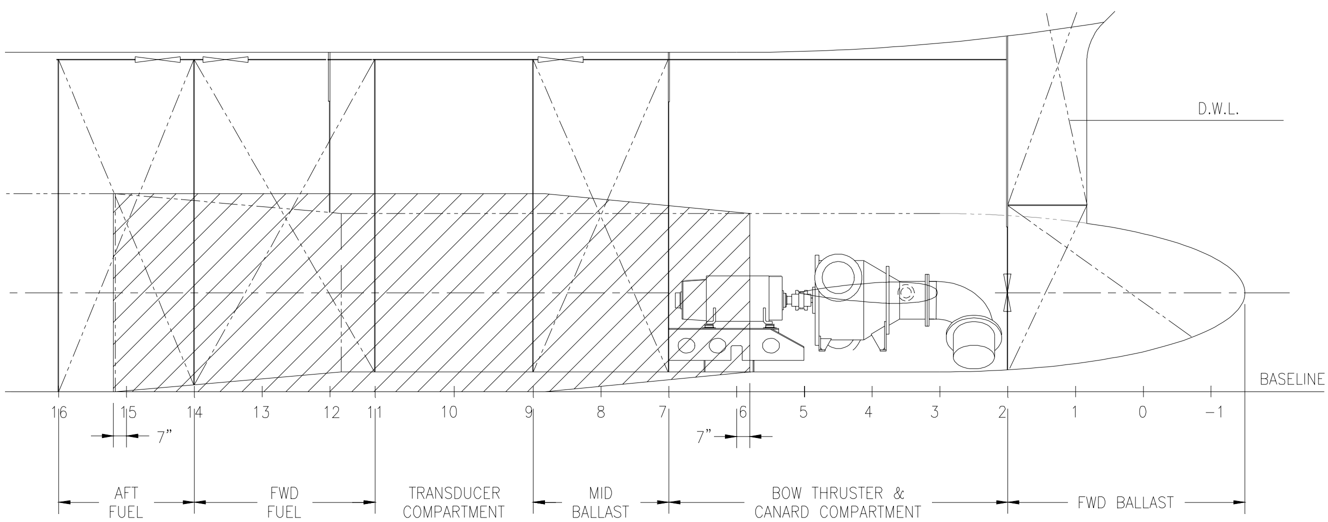

Figure 11. ***R/V Western Flyer*** **– Pontoon Modifications**

Instead, we had to develop a method of construction that allowed the new notch structure to be assembled in place on the vessel. One of the possible solutions involved eliminating the strut side between the tank top and the intersection of the new fairing pieces and the strut side. This solution would have increased the accessibility to the area outside of the struts and inboard of the new fairing piece, making the welding much easier. Unfortunately, the finite element model indicated that the proposed geometry did not meet the structural requirements.

The final design is similar in geometry to the original modular concept, except that the flanged plate is intercostal between the existing frames. The final construction method involved the following procedure:

1) The existing shell plate is removed.
2) The existing frames and bulkheads are then inserted with new plate to extend the frames out to the new shape of the haunch.
3) The extension of the strut side/closing plate are then fitted to be intercostal between the frames.
4) The intercostals are then temporarily removed so that the shell plate can be welded to the new frame shapes.
5) The intercostals are then reinstalled and welded to the existing frames and new shell fairing plates using full penetration welds with backing bars.
6) The final closing welds of the shell plate are made from the outside using an internal backing bar, thus eliminating the need to have access to both sides of this weld.

This design gave the yard the flexibility to easily fit the new notch structure to the existing shape of the vessel.

Lifting/Blocking

R/V Western Flyer was lifted using two floating cranes and set down on specifically constructed ways. The two cranes were needed to lift her at six points. Finite element analysis of the vessel in both the lifted and blocked conditions showed no extreme stresses.

The blocking analysis also involved determining the extent of existing structure that could be removed at a given time, and the sequence in which the removal could take place. Once again the finite element model was used as guidance in establishing the structural removal criteria the yard would have to follow. One of the primary concerns was that there might be large stresses built into the vessel during construction, and that, once the plate began to be cut, she would assume a new shape. Another concern was that the vessel might have to withstand an earthquake while on the ways. The initial reaction to these problems was to limit the amount of plate removal, not allowing the vessel to develop large deflections caused by the release of built-in stresses, and maintaining her structural integrity in the event of an earthquake. However, being overly conservative can needlessly delay the project, pushing back the delivery date as well as driving up the cost.

Working closely with the yard, we established a work plan that would allow work to progress at an acceptable rate, while maintaining sufficient structure integrity to withstand most unforeseen circumstances. The yard removed the notch structure, including the shell plating and the frame inserts, in segments up to 28 feet in length. Removals were permitted on both sides of the port and starboard strut. The removed segments were also to be directly across from each other, or as nearly so as possible. For example, if the structure was removed from Frames 15 though 23 on the outboard side of the strut, then the removals would cover the same span on the inboard side. To offset the strength lost from the removals, bracing was added from the lower hulls to the cross deck and ways.

In addition to the bracing, a dimensional control system was established. The yard would measure marked points on the boat to fixed points on the ways. Measurements were taken once a week, consisting of horizontal measurements from a point on the lower hulls and diagonal measurements taken to a point on the strut. The recorded measurements showed that the shape of the vessel changed very little during the structural modifications.

Interferences

There were many interferences between the existing machinery systems and the new structure being installed. In most cases the new structure was modified to have minimal impact on the existing systems. The weight impact of any proposed changes were always considered in developing possible solutions.

Expanding Capabilities

As *R/V Western Flyer* was to be in the yard for an extended period, MBARI has taken the opportunity to expand her capabilities, as follows:

1) Grid coolers were incorporated into the lower hull modifications. This reduces maintenance by replacing the seawater cooling system with fresh water. These grid coolers are sized for zero speed and serve the HVAC, refrigeration and hydraulic systems.
2) The weight of the ROV *Tiburon* was approaching the limits of the existing crane in the moonpool bay. As the foundation for the crane was to be modified, MBARI decided to replace the existing HIAB 290-2 with an Effer 62 crane, increasing the lifting capacity of *Western Flyer* to 62 tonnes. This change required a large portion of the cross deck in way of the crane to be replaced with much heavier structure to support the larger crane capacity.
3) A taut wire system was added to the moonpool bay area. This system includes a depressor weight and winch, and aids in the retrieval of the ROV.
4) In an effort to extend the range of *Western Flyer*, the area below the aft well deck has been converted to a fuel tank.
5) Sound insulation was added to many of the ducts and areas surrounding the moonpool. Noise dampers were also added to the hydraulic system, the resilient mounts of the diesel generators were upgraded and the engineroom fans will now be attached via resilient mount.

SUMMARY

The vessel was delivered in the summer of 1999. This project was exceedingly challenging for the shipyard and MBARI staff. They worked closely together to resolve the various issues that arose. The finite element models proved very useful in not only determining the extent of the modifications but in determining the type and extent of rip-out that could be accomplished during construction.

The authors would like to take this opportunity to thank Bay Ship and Yacht and the crew of *Western Flyer* for their input, guidance and insight throughout the project.

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