Millennium Class Tanker Structural Design – From Owner Experience to Shipyard Launching Ways

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ABSTRACT

Three 125,000 DWT double hull tankers are currently under construction for ARCO Marine, Inc. at Litton Avondale Industries in New Orleans, LA. These Millennium Class tankers are being built to transport crude oil from Valdez, AK to Cherry Point, WA. The design satisfies the requirements of OPA 90 and incorporates a unique structural design philosophy intended to enhance the structural performance of the vessel. This paper will illustrate how the Owner's experience with previous vessels in Gulf of Alaska trade is reflected in the structural design of the new ships. The human elements of safety, inspection and maintenance are discussed and the influence of these factors on the structural arrangement is highlighted. In concert with these human factors are structural design improvements that have been implemented to specifically address fatigue and stress cracking with the intent of reducing repair requirements. These topics are presented in a discussion that follows the structural design from concept, through design and analysis and into the construction of the vessels. Lessons learned throughout the process are presented.

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FOREWORD

The goal of this paper is to broadly illustrate the process by which the structure for the Millennium Class tankers was conceived, designed and constructed. Design and construction of the vessels are addressed from both a technical and a non-technical viewpoint. The project has been an exercise in philosophy, engineering and project management, and it is our hope to provide an insight to the successes and pitfalls on a first-of-class ship construction project.

INTRODUCTION

ARCO Marine, Inc. (AMI) is a wholly owned subsidiary of the Atlantic Richfield Company (ARCO). AMI is the marine operating company responsible for carrying ARCO's crude oil produced on Alaska's North Slope to ARCO's refineries on the U.S. West Coast. Crude oil is loaded at the terminal in Valdez, Alaska and transported to refineries in Cherry Point, Washington and Los Angeles, California.

AMI currently operates a fleet of six tankers (five crude, one product) ranging in size from 50,000 DWT to 265,000 DWT. In 1998 and 1999, the Oil Pollution Act of 1990 (OPA '90) forced the retirement of three AMI 120,000 DWT vessels. These single hulled ships moved crude oil from Valdez to Cherry Point since the opening of the Trans-Alaska Pipeline Service (TAPS) in 1978. OPA '90 will also require that AMI retire two 265,000 DWT vessels in the year 2000.

In the early 1990's AMI began to consider options that would replace tonnage lost due to OPA '90. AMI explored all options including retrofitting existing tankers with double hulls, fitting completely new forebodies, and building new vessels. Ultimately the decision was made to construct new vessels, the Millennium Class Tankers.

The full effort towards preliminary design of the Millennium Class tankers commenced in 1996. In July 1997 a contract was signed with Avondale Industries Shipyard Division, now Litton Avondale Industries. Detailed design commenced immediately and the keel was laid in May 1998. The first ship, the *ARCO ENDEAVOUR*, is scheduled to deliver in the fourth quarter of 2000. The contract currently provides for a total of three Millennium Class tankers.

Decision for Newbuilding

Maintaining the size of the AMI fleet necessitated plans for replacement of tonnage phased out by OPA '90. Initial exploration into possibilities for obtaining double-hulled vessels yielded three options; retrofit of double hull to an existing ship, replacement of a complete forebody, or new building. Retrofit of a double hull into existing

vessels was quickly dismissed. Cargo capacity lost in retrofitting an inner hull to an exiting 120,000 DWT vessel was impractical. It was also understood that the outer hull, while in good structural condition, would remain as part of the hull after 20+ years of Alaskan trade.

Forebody replacement presented a more promising option than retrofit as it provided completely new structure in the cargo block. However, while more desirable from a structural standpoint, the loss in tonnage from the previous 120,000 DWT vessels would still be incurred. Lengthening of the vessels was considered but forward visibility limitations and an increased length to depth ratio limited the feasibility of this additional modification.
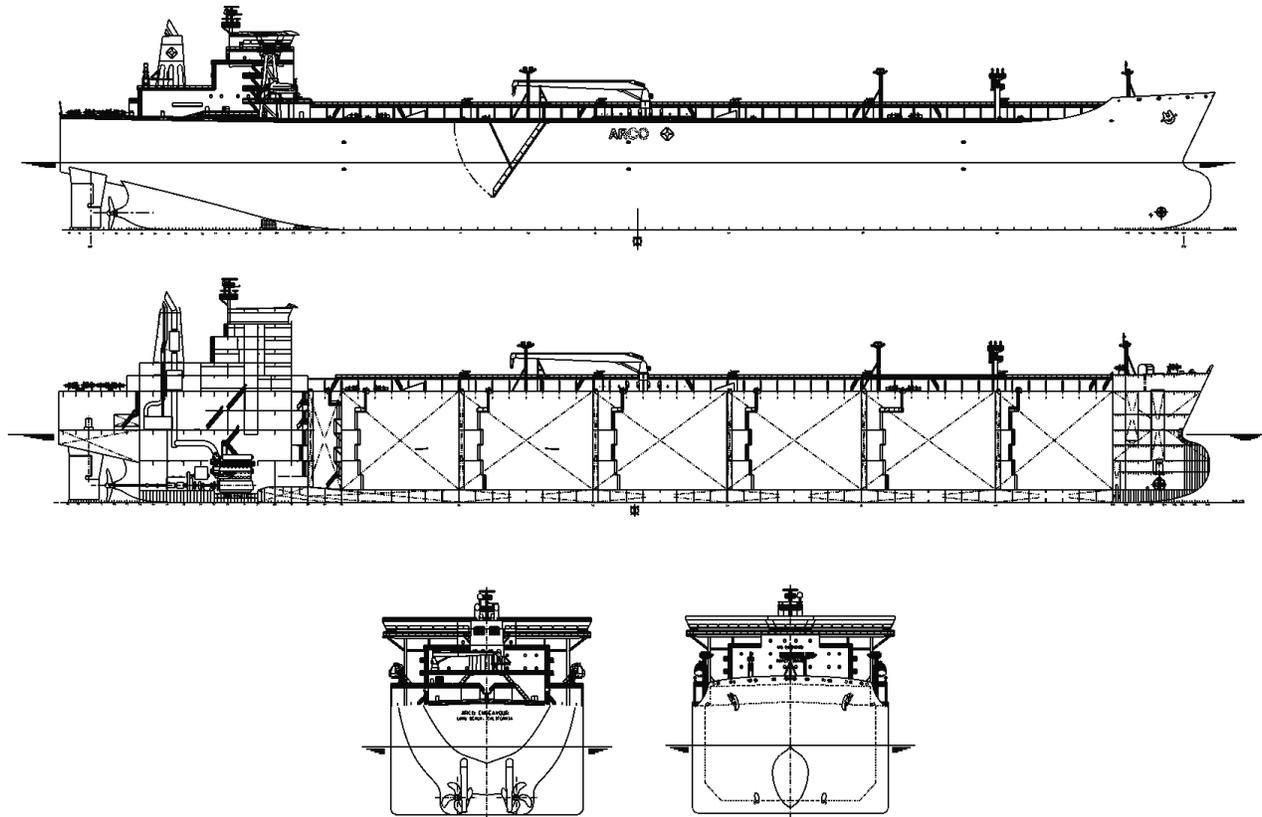
The forebody option would also have required the retention of an inefficient steam propulsion plant. As a major retrofit, forebody replacement would necessitate installation of new cargo control and gauging systems as well as new deck machinery. Along the same lines, it would be desirable to upgrade the navigational systems to more modern bridge equipment. In the end, with safety, efficiency and economic consideration given careful attention the forebody option was dismissed and the decision was made to pursue new-build ships.

Design Team

AMI embarked in pursuit of a new design by bringing together an experienced and highly qualified structural design team. From the early stages AMI began to work closely with a number of consultants to ensure that the base of experience was extended as widely as possible. The main consultants, John J. McMullen Associates, Inc. (JJMA), MCA Engineers, Inc. (MCA), and Herbert Engineering Corp. served as collaborative design consultants throughout the initial phases of the project.

The intent of this team approach was to draw from unique skills that each consultant brought to the table. JJMA served as the primary consultant and provided broad-based naval architecture, marine engineering and cost estimating expertise as well as recent international experience with double-hull tanker design programs. MCA contributed with a strong background in structural design analysis and significant historical experience with vessels in the existing AMI and Alaskan tanker fleet. Herbert Engineering provided expertise in specific issues relating to stability, subdivision, and other factors such as ballast exchange. This team was responsible for the general development of the Contract Specification and continued to work together throughout the design and construction phase.

In preparation for contract signing, AMI chose to approach the final stages of preliminary design as a teaming effort with the consultants and Avondale Industries Shipyard Division, now Litton-Avondale

Fig. 1 Inboard Profile, Outboard Profile, Bow and Stern Views

Shipyard. At the time of these meetings the concept and preliminary design had been developed to clearly represent Owner requirements. The goal of teaming with the Shipyard was to ensure Owner requirements and Shipyard capabilities were compatible and fully incorporated in the detail design.
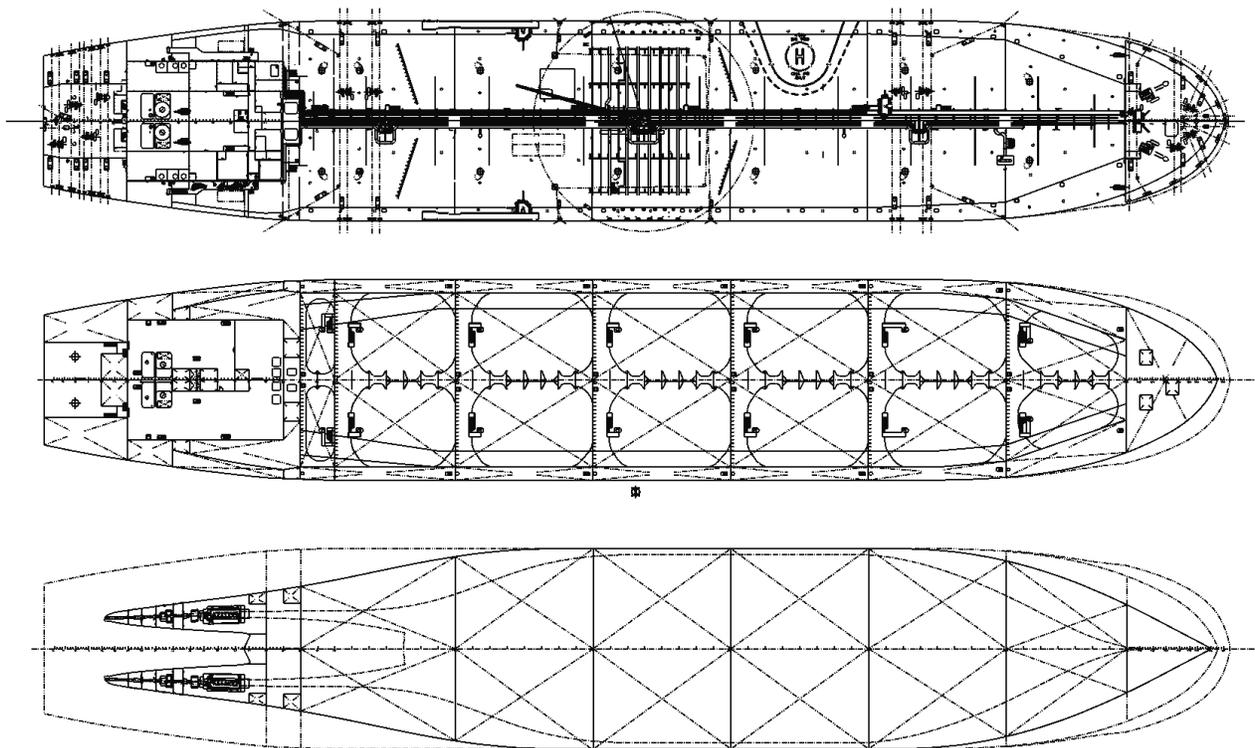
STRUCTURAL DESIGN PHILOSOPHY

A number of key issues relating to the structural design were identified following the decision to pursue construction of new ships. Safety, reliability, proven design, necessary fatigue life and maintainability were all cited as issues to be addressed in the design process. Strong consideration was given to the fact that the trade routes served by the AMI crude oil tankers are among the most severe operating environments in the world, and require a significant amount of time spent in the waters of the Gulf of Alaska. Features specific to AMI were also to be incorporated into the design based on 20 years of experience transporting crude oil in Gulf of Alaska waters.

The design centered on a belief that designing for prevention is the safest and most economical approach in addressing the long-term operation of tankers. In short, the primary theme of process was "an ounce of prevention is worth a pound of cure." The overall intent was not to build a ship that just met the Rules of Class. The intent was to construct a vessel that would meet or exceed the Rules as required, to a degree that the vessel became uniquely suited to meet the Owner's need for extended service in a severe environment. Most importantly, it was felt that future problems could be avoided by turning to past experience as a learning tool. Past experience with ship structure became a key factor in development of the detail design [1-4].

Learning from Experience

Contributing greatly to AMI's understanding of fatigue cracking and monitoring of ship structure was the United States Coast Guard's Critical Area Inspection Program (CAIP) [5]. Existing AMI vessels had been operating under this program since its inception in 1991. As a result, AMI had developed a clear plan for the "management" of structure on existing vessels.

3

Fig. 2 Upper Deck Plan, In-Tank Plan and Plan on Tank Top

Significant amounts of data have been collected and AMI continues to support a proactive, rather than reactive, response to fatigue issues in the structure of its existing ships.

Historically, AMI's database of experience with structural details extends back through 1987. Locations, lengths and types of fractures were documented. Patterns of structural fatigue cracking were clearly identified and problems were remedied with the development of structural fixes through finite element analysis. Participation in this program has undeniably led to greater understanding of designing for fatigue in ship structure.

Also helpful in determining potential problem areas were the various diverse experiences of the design team members. This experience combined with informational resources published by the industry led to a better understanding of the past performance of a variety of structural arrangements. Particularly noteworthy among published data are publications by the Tanker Structural Cooperative Forum (TSCF) [6,7], Oil Companies International Marine Forum (OCIMF) [8] and Lloyd's Register [9].

"Ground Rules"

For the Millennium Class tankers, the structural design was to be developed based on extensive engineering. AMI required that the ships be designed for a 30-year fatigue life. This included not only compliance with ABS' SafeHull A and B programs, but also finite element analysis, structural fatigue analysis and compliance with ABS' Dynamic Loading Approach (DLA) [10,11]. During concept design preliminary structural details were studied extensively in areas historically known to experience structural fatigue cracking. This preliminary analysis was completed prior to contract signing.

Based on AMI's Alaskan operating experiences, a number of design criteria were established for the structure. The vessels were to be built primarily with mild steel, with little or no reduction in scantlings. Where high strength steel was used margins above regulatory allowable minimums were typically applied. Critical structural areas were studied extensively by finite element analysis, dynamic load analysis, and spectral fatigue analysis. This conservative approach led to a number of decisions that resulted in a rugged yet functional design.

Addressing Fatigue in Structural Design

One of the most significant conceptual efforts made in the design was to address fatigue in structural details. Clearly, it is acknowledged that design and analysis cannot yield a zero crack condition. However, due diligence and attention to known problems can yield a greater understanding of those structural details to avoid and those details to incorporate. In some cases, details that performed poorly in previous vessels (e.g. mushroom shaped cutouts at erection joints) were redesigned for acceptable performance in new vessels.

The trade route to be traveled by the Millennium Class tankers presents a somewhat unique fatigue life profile. Nearly all of the at-sea operation of the vessels will be in North Pacific waters. Port time spent during loading and discharge is minimal and each ship will average a round trip about every 10.5 days. To illustrate the exclusivity of trade and frequency of voyages, the 120,000 DWT vessels recently retired each completed over 600 voyages to Valdez in approximately 20 years of operation.

CONCEPT DESIGN

Size of Vessel

The decisive commitment to build new vessels turned the focus towards clear definition of a design philosophy under which the vessels would be built [12]. Size of the vessel was the first issue to be addressed. The primary trade route for the proposed Millennium Class tankers is to be between Valdez, Alaska and Cherry Point, Washington. Because this trade extends into Puget Sound, Washington a deadweight limit of 125,000 DWT is mandated. This restriction, imposed by U.S. Coast Guard regulations excludes tankers of greater than 125,000 DWT from delivering oil to U.S. ports in Puget Sound, Washington [13].

While USCG regulations will ultimately govern the deadweight of ships entering into Puget Sound the overall cargo capacity of the Millennium Class tankers was set at one million barrels. This corresponds to roughly 137,000 DWT of Alaskan North Slope crude oil. The choice was made to proceed with a vessel of this size in an effort to enhance its overall trading versatility during the planned 30-year service life. Thus, the vessels have been designed to a scantling deadweight of 137,000 MT but will operate at a deadweight of 125,000 LT when delivering crude oil into the Puget Sound. Table 1 provides further Principal Characteristic information.

Cargo Block Structural Configuration

The overall vessel and tank configurations are shown in Figures 1 and 2. The cargo tanks are arranged six tanks long by two tanks across with two slop tanks located just aft of the No. 6 cargo tanks. The ballast tank arrangement includes six pairs of J-tanks with the No. 6 tanks extending aft beneath the slop tanks. It was found that this arrangement provided an optimum operational configuration in terms of intact and damaged stability.
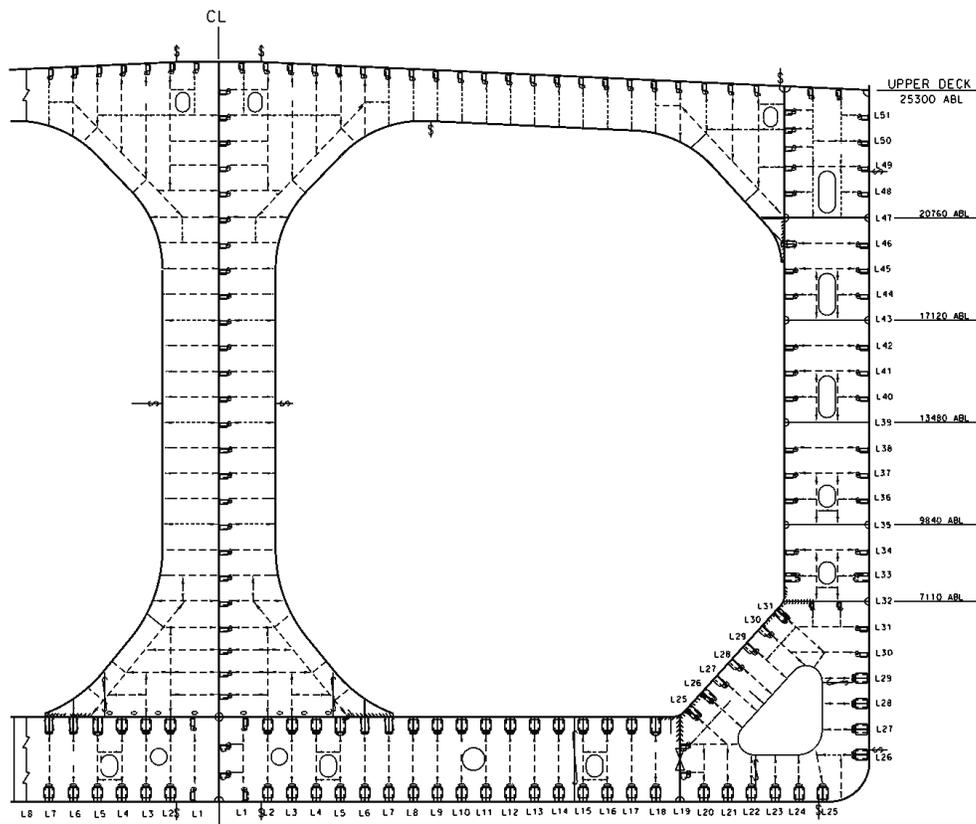
The Midship Section is shown in Figure 3. Transverse web frame spacing is 3.96 meters and typical longitudinal spacing is 862 millimeters. Web frame structure is balanced on either side of the centerline bulkhead with longitudinal stiffening on the starboard side of the bulkhead. Main longitudinal girders are the centerline vertical keel and girders port and starboard beneath the lower hopper radius. Two horizontal stringers support the transverse bulkheads in the cargo block and are shown in Figure 4. Five longitudinal stringers are included in the ballast tank wing walls and the second and fourth stringers coincide with the cargo tank horizontal stringers.

Of special note is that a continuous, watertight, full height, centerline bulkhead runs below the Upper Deck (strength deck) from the collision bulkhead to the transom. The sole exception to the tightness of this bulkhead is found at the athwartship access in the cargo pump room. Otherwise, the centerline bulkhead divides the cargo block into the port and starboard ballast and cargo tanks and the engine room machinery spaces into two completely separate and redundant engine rooms.

The after portion of the centerline bulkhead, watertight and insulated to an A-60 standard, is also continuous in the machinery spaces and engine room casing above the Upper Deck and continues upward to the top of the stack. Three sliding, watertight A-60 doors, normally closed, are found in the machinery spaces and are available for athwartship access. The continuity of the centerline bulkhead continues forward of the collision bulkhead to the stem but is not watertight in this area.

Table 1 Principal Characteristics

Length, Overall	272.69 m
Length, Between Perpendiculars	258.16 m
Beam, Molded	46.20 m
Depth, Molded (at Side)	25.30 m
Depth, Molded (at Centerline)	26.30 m
Displacement, Design	159,100 MT
Draft, Design	16.31 m
Draft, Scantling	17.50 m
Lightship Weight	33,188 MT
Displacement, Design	160,778 MT
Displacement, Scantling	173,310 MT
Cargo Capacity, Design	899,757 bbls
Cargo Capacity, Scantling	978,032 bbls
Gross Tonnage	85,093 MT
Net Tonnage	36,299 MT
Block Coefficient, Design Draft	0.830
Design Speed	16.5 knots

Fig. 3 Typical Midship Section

"Hopper" Design

A significant research effort was made during the preliminary design to explore possible variations on the "hopper" design. The "hopper" is the area of sloped plating at the outboard lower corner of the cargo tanks. It was known that the most critical area of design in this configuration is found in the lower hopper transition.

Options for the connection at the lower hopper included use of a cruciform weldment, a cruciform casting, continuation of the inner bottom plating past the hopper to the side shell, or a radius hopper plate supported by a longitudinal girder. The final decision was to incorporate a radius plate at the corners of the hopper. Rationale for this decision included finite element analysis, past structural experience documented in the TSCF and Lloyd's publications, ability to hold construction tolerances, and overall stiffening arrangements.
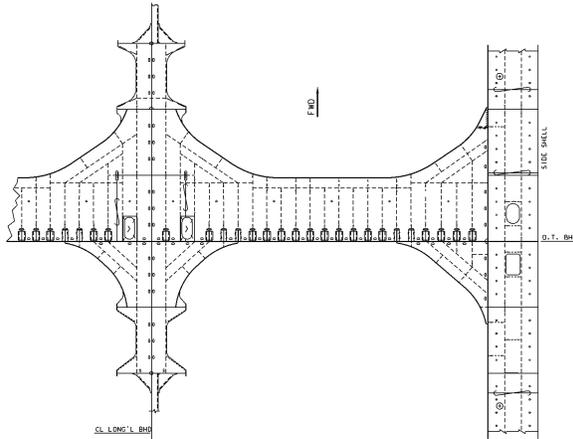
Forebody and Afterbody Structure

The innerbottom plating and the five-stringers in the ballast tanks transition into the flats in the engine room. These levels also extend forward into the bow thruster and forepeak areas. The tank top structure carries aft as the flats of the Pump Room and the lower Engine Room. The major stringer at 9840 mm above baseline (ABL) transitions into the upper Engine Room and Purifier Rooms. The major stringer at 17120 mm ABL carries aft and forms the machinery flat for much of the auxiliary machinery, the Engine Room workshop and a large spare parts storage area. Finally, the ballast tank stringer at 20760 mm ABL slopes upward approximately one meter and forms the flats in the port and starboard Machinery Control Rooms.

HUMAN FACTORS – SAFETY, INSPECTION, AND MAINTENANCE

Special attention was given to the arrangement of structure as it pertains to the human element in design. Specific issues that were addressed in the cargo block included emergency removal of personnel, means of standard access and egress from tanks, ability to adequately ventilate tanks, and access for tank inspection

6

and maintenance. In the machinery room consideration was given to equipment removal and maintenance.

Fig. 4 Transverse Bulkhead Stringer at Midship

Safe Access and Ventilation

Features included in the ballast tank design allow for safe access and proper ventilation during tank entry procedures. IMO and SOLAS guidelines for access in tanks were rigorously applied as were ASTM standard practices regarding ladder and platform construction [14-16]. Inclined ladders are located at the forward outboard corners of the ballast tanks and provide primary access. A vertical access trunk with a vertical ladder is located at the aft inboard corner of the tank. Finally, at the aft outboard corner of the tank is a second 600 mm x 800 mm clear opening for personnel and stretcher removal. This opening extends through each stinger level to the bottom of the tank.

Cross-ventilation is to be provided by locating portable fans at the vertical trunk or the personnel removal hatches. An additional provision for ventilation is included with the attachment of a ventilation fan to a branch line on the ballast main that may be used to ventilate back through the suction/fill lines into the tanks. Bolted tank cleaning openings are provided in every other frame bay to facilitate cleaning of sediment from the tanks or, in the event of a leakage from the cargo tanks into the ballast tanks, the cleaning of oil from the tank via portable tank washing machines.

Access into cargo tanks is provided via a hatch at the aft end of the tank. A vertical ladder provides access down to the first intermediate platform. This ladder is hinged so that it may be moved clear of a 600 mm x 800 mm clear drop opening to the bottom of the tank. Inclined ladders extend from the intermediate platform down to both horizontal stringers and to the bottom of the tank. Handrails are provided on each stringer as required by IMO guidance.

Finally, a bolted manhole is located in the forward and aft tight bulkhead of each cargo and ballast tank in the cargo block. The manhole consists of a 24 inch pipe with a 150# bolted blind flange that is hinged for handling. The manholes, which would be opened only during shipyard repair period, provide two additional means of access and egress from each tank.

Cleaning of Cargo Tanks

Cleaning of cargo tanks is benefited by the inclusion of most major longitudinal structure within the ballast tanks. The result is "clean" bulkheads in the cargo tanks. Longitudinal structure in the tanks is found at the upper deck and the starboard side of the centerline bulkhead, which carries the centerline longitudinal structure. The aft bulkheads have two horizontal stringers and carry the vertical transverse bulkhead. This arrangement effectively results in four clean surfaces in the port cargo tanks and three clean surfaces in the starboard cargo tanks.

It is worthy of note than the IMO standard for coverage was enhanced in the ship specification to facilitate safer tank entry and to assist in cleanup for shipyard repairs [17]. This higher standard required direct impingement from the crude oil wash machines on 95% of the primary and the secondary structure (i.e. bulkhead longitudinals and vertical bulkhead stiffeners). Three top and two bottom machines in the starboard side tanks and three top and one bottom machine on the port side tanks were used to meet these criteria.

Access and Maintenance in Machinery Spaces

Special efforts were made to include provisions in the design that facilitated maintenance and removal of equipment in the engine room and machinery spaces. Clear vertical accesses to the exterior are provided through the decks on the starboard side of the Pump Room access trunk and in both Engine Rooms. A ten-ton stores crane located on the exterior "B"-Deck services the port side Engine Room access. A five-ton air hoist services the starboard side Engine Room access. Underdeck bridge cranes service each of the two main engines and are capable of transporting equipment to common lifting points at the vertical accesses.

An extensive monorail system in each Engine Room is capable of reaching most auxiliary equipment and transporting it to the port side Engine Room Workshop for servicing or to the vertical accesses for removal from the ship. Bolted equipment removal plates on the 17120 mm ABL machinery room flat allow access to the cargo pump motors located on the 9840 mm ABL engine room flat. Again, the monorail system allows for removal of these eight-ton motors from the port side of the ship. A watertight, A-60 insulated and normally-closed bolted equipment removal plate (BERP) is located in the Engine

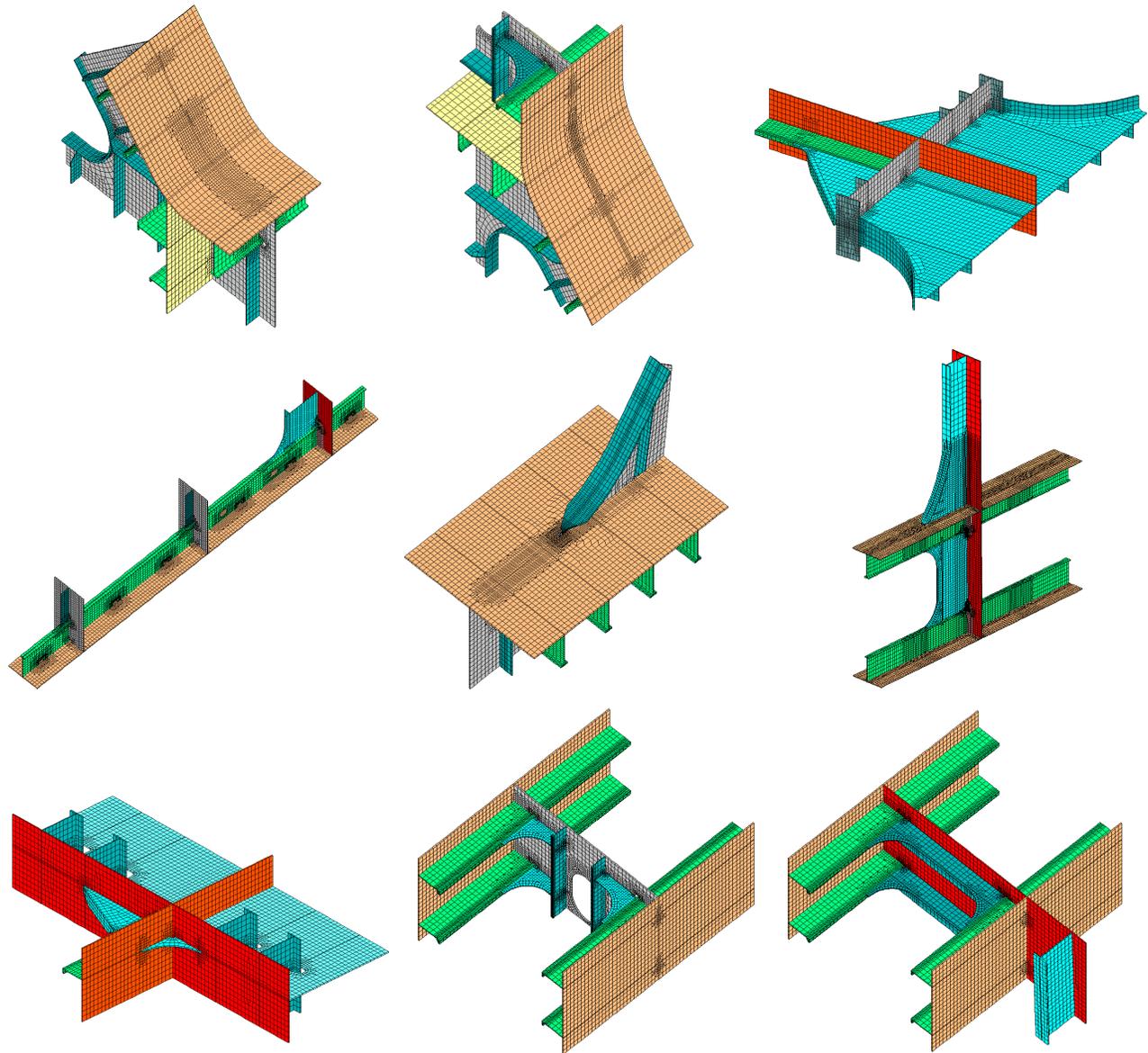Room Workshop to facilitate the athwartship movement of large equipment across the ship.

PRELIMINARY DESIGN

The overall scantling arrangement and Midship Section were developed and analyzed using ABS SafeHull and separate coarse meshed finite element models of the midship section. The separate finite element analysis telescoped from global to intermediate and then to general local models.

Nine Critical Details Addressed

The main objective in analyzing critical structural details was to identify and implement any potentially large structural changes prior to turnover of the design to

Fig. 5 Nine Local Details in Preliminary Analysis (Top row, l to r: Lower Hopper, Upper Hopper, Stringer at Centerline Bulkhead; Middle Row, l to r: Bottom Longitudinal, Transverse Web Frame at Tank Top, Double Bottom at Transverse Bulkhead; Bottom Row, l to r: Horizontal Stringer at Transverse Bulkhead, Inner and Outer Shell at Transverse Bulkhead, Inner and Outer Shell at Web Frame)

the Shipyard. Further, the owner also wanted to have timely and complete control in selecting the sensitive structural details to be used repeatedly throughout the cargo block. This is again a reflection of extensive experience with existing ships operating in the harsh TAPS trade environment, which has demonstrated that the design of the local details ultimately determines the probability of premature fractures. Concurrent with concept design, numerous design variations were analyzed in common structural details to optimize and improve their structural behavior.

Nine local details found in the midship section were selected and analyzed using detailed solid element mesh. The mesh size was on the order of the plate thickness in the critical regions. The nine details are shown in Figure 5 and cover typical problematic construction details. The models were analyzed using eight initial design load conditions. These consisted of four loading conditions: Full Cargo, Ballast and two "Checkerboard" loading conditions. The Full Cargo and Ballast loading conditions were analyzed in still water, head-sea design hog and head-sea design sag waves, while the two Checkerboard conditions were analyzed in still water only. The design wave used had a length equal to the ship's LBP and a wave height of 8.05 meters.

Results of Preliminary Analysis

The preliminary analysis revealed the existence of high general stresses in the two horizontal stringers when subjected to the checkerboard loading conditions. The stresses were too high to be eliminated by local reinforcement, and the need for modest changes to the stringer design was identified. The modification required additional and symmetric transition structure aft of the transverse bulkhead. Forward of the transverse bulkhead the stringer transition was softened at the centerline and longitudinal bulkheads and extended forward by one additional frame.

The results also included the identification of two alternative side shell longitudinal to frame connections. The first involved the use of an offset panel stiffener with a sophisticated web frame collar design. The second involved the use of soft-toed brackets butt-welded to the bulb-section of the side shell longitudinal on both sides of the frame. The latter of the two details was chosen for use on the vessel based on construction preference.

Other recommendations included improvements to the lower hopper design, including rearrangement of the hopper longitudinal, a reduction of the hopper radius and increased web frame thickness in way of the hopper. It was found that the radius plating in the hopper design, when subjected to a sagging condition and without proper support, tended to "shrink" similar to the radial contraction of a pipe subject to stretching. The

deformation in the hopper plating was restricted at the web frame thereby creating high stresses in the welded connection of the web frame to the hopper plating.

Also noteworthy in the findings was the need for additional support to improve the effectiveness of the curved sections of the web frame faceplates. Without additional bracket and flatbar support the curved section of the web frame faceplates become ineffective, resulting in unacceptable stresses in the web frame and flange at these locations.

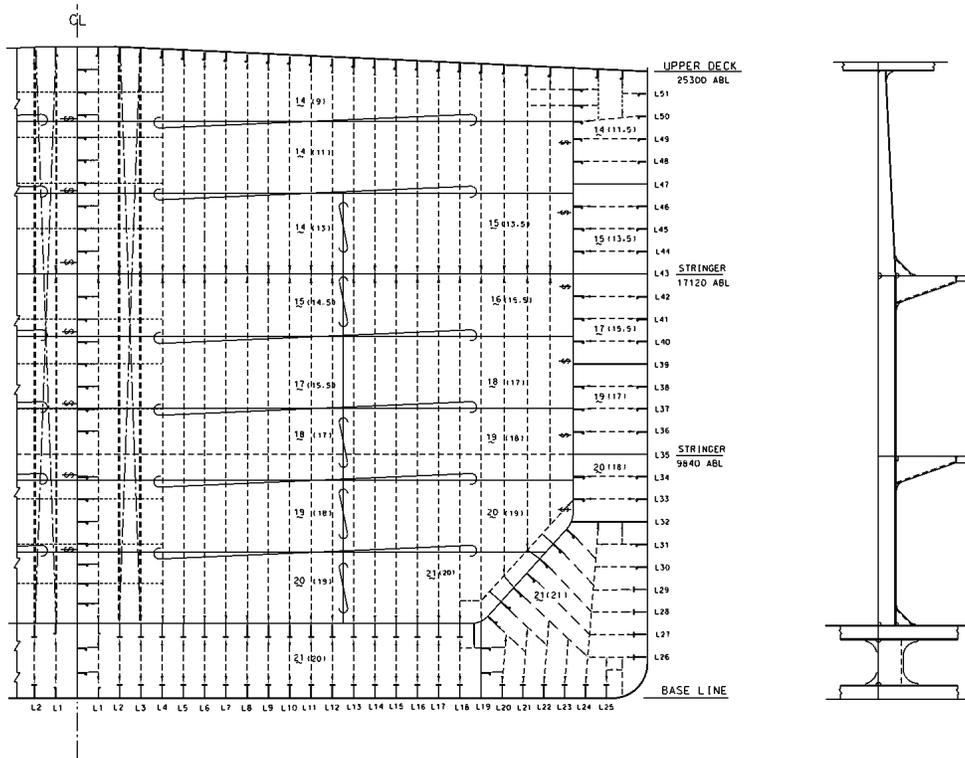**Use of Mild vs. High Tensile Steel**

The rationale for the decision to tend towards use of mild steel was based on historical problems encountered with the liberal usage of high tensile steel in ships. In the 1970's and 1980's the movement of the shipbuilding industry to look towards high strength steel as a means for reducing the overall weight, and therefore cost, of the vessel created many problems. Credit was taken in hull scantlings as high tensile steel allowed higher allowable stresses. In many cases, particularly for ships operating in less severe trade routes, this was acceptable. However, vessels frequently subjected to a harsh environment resulting in moderate or high cyclic stresses, developed fatigue cracks in the structural transition details.

In a distinct effort to avoid chronic fatigue problems it was decided that mild steel (ABS Grade A) would be used for all structure except in areas which specifically required high tensile steel. If high tensile steel were to be used, a reduction in scantling would be allowed, providing there was a minimum ten percent allowance above the ABS requirements, including corrosion allowance. For the upper deck, where the inherently low neutral axis of double hull construction results in mild steel plate thickness well above 25 mm, the deck is constructed of ABS Grade DH plate. However, by using Grade DH plate, ABS rules allow for a plate thickness of 19.5 mm, including corrosion allowance, but 22 mm plate was used. A second example of the use of high tensile steel is in the horizontal bulkhead stringers, which are subjected to high static stress but relatively low cyclic stress.

Figure 6 illustrates the application of these criteria to the design. ABS Rule minimum scantlings are shown in parentheses with the as-built plate scantlings shown outside the parentheses.

Fixed Range for Scantlings

For structure in the cargo block, in fuel oil tanks, and in miscellaneous ballast tanks a "rule of thumb" was set for determination of minimum and maximum scantlings. Structural steel was limited to a minimum of 12 mm in thickness and was to be no greater than 25 mm in thickness. In the case of the minimum scantling,

Fig. 6 Transverse Bulkhead Arrangement Showing Scantlings (l), Typical Bulkhead Stiffener (r)

experience showed that steel less than 12 mm proved sensitive to corrosion. For the maximum scantling, steel greater than 25 mm reduced the benefit of the steel's ductile behavior and thereby reduced the inherent redundancy of the structure [21]. Thick plates create a 3-D stress field at a potential crack tip, making the steel more brittle. From a maintenance standpoint, the relatively limited availability of steels thicker than 25 mm can problematic in repair yards.

These decisions were made based on past experience in vessel operation and with extensive preliminary finite element analyses complete. Ultimately, as design progressed, it was found that in only a very limited number of cases would material less than 12 mm have been of benefit or met the fatigue life requirements.

Finalization of Preliminary Design

The preliminary phase in the design process was closed with JJMA as the lead technical coordinator. This effort included modifying and updating the concept design Midship Section and Scantling Plans. Modifications were based on the findings of the structural finite element analyses and included additional changes desired by the Owner. The finalization of this phase also included extensive review of the complete concept design with all consultants present. This combined effort

allowed all participants to benefit from the extensive experience of the group as a whole.

Prior to contract a fully developed set of lines, a Midship Section and a General Arrangement were turned over to Avondale. An overall teaming effort was initiated at this point in time. The Midship Section and a preliminary Scantling Plan were modified slightly and tailored to meet specific requirements demanded by Avondale's production scheme. These modifications were small in nature and generally were the result of plate straking and erection butt location. All modifications were completed with the approval of AMI and the consulting team.
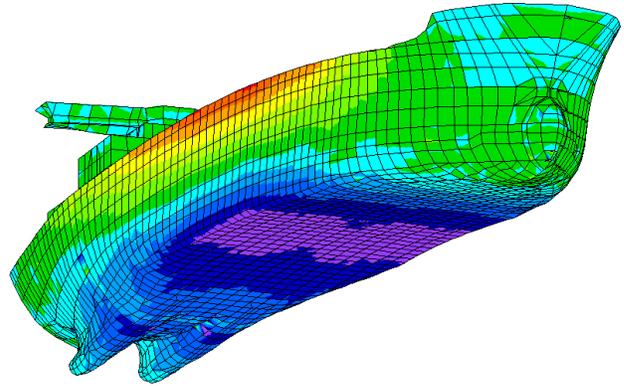
SafeHull

Following contract signing, work quickly advanced on design issues related to Class approval of the structural arrangements. These activities included the running of ABS' SafeHull Phase A and Phase B. Because much initial work had been completed on the structural design, SafeHull served almost exclusively as a verification tool rather than as a design tool. The design was based on good engineering practices and did not rely on SafeHull as a tool to find minimum allowable scantlings.

In Phase A, the rule-based initial scantlings were verified and shown to satisfy the SafeHull prescribed load strength and fatigue requirements. In Phase B, strength

assessment of global and local structure was verified using SafeHull imposed loads. Here, global structure was addressed as a coarse mesh, three-tank model. Local structure was addressed as two-dimensional fine mesh models.

Limited modification to the structure was necessary based on the results of SafeHull. Plate scantlings at the toes of the cargo tank horizontal stringers required some increase, as did the local longitudinal bulkhead in way of these toes. Panel breakers were necessary in some instances to meet small panel buckling criteria. All necessary modifications were made and the resultant changes to structure were turned over to MCA for incorporation into the DLA analysis.

DYNAMIC LOAD APPROACH (DLA)

Analytic Approach

Concurrent with the Shipyard effort to run SafeHull, MCA Engineers commenced work on the ABS' prescribed Dynamic Load Approach (DLA). The DLA analysis was based upon standard ABS procedure, but using MCA-developed finite element models and *SPLASH*-generated wave-induced pressure profiles. *SPLASH* is a 3-D panel code for computing inviscid, irrotational potential flows [18]. This procedure included the following steps:

1. *Selection of four worst-case loading conditions.*
   Loading cases selected and shown in Table 2 were:
   - Alaskan Crude, typical full load condition.
   - Heavy Ballast, typical ballast condition
   - Arrival in San Francisco, a partial loaded condition
   - Checkerboard #6 SWB, a checkerboard loading condition per ABS.

Fig. 7 Global FEA Model

2. *Calculation of the long-term extreme value of the Dominant-Load-Parameters (DLPs).*
   This was accomplished using the ABS-specified H-family weather spectra and *SCORES II*-derived Frequency Response Functions. *SCORES II* is a strip theory ship motion program used by ABS for the DLA analysis [19]. Four Dominant-Load-Parameters were calculated per ABS guidance; hull girder bending moment, roll angle, vertical acceleration forward, and lateral acceleration forward.

3. *Calculation of the equivalent waves for each load case and Dominant-Load-Parameter combination.*
   These were determined by dividing the long-term Dominant-Load-Parameter extreme values by the *SPLASH*-generated Frequency Response Functions to determine the equivalent wave heights. The *SPLASH*-calculated Frequency Response Functions were generated based on the equivalent wave systems (headings and frequencies) derived by the *SCORES II* results. The external wave pressure and internal tank pressure profiles were then multiplied by this scaling factor to obtain the finite element model loading profile. The results of this phase are shown in Table 3.

Table 2 - Dominant Load Parameters

Case #	Load Case	Wave-induced Bending Moment [MT-m]	Roll [degrees]	Vertical acceleration [m/s^2]	Lateral acceleration [m/s^2]
14	125K Alaskan Crude	656350	20.2	5.463	2.054
27	Heavy Ballast	586660	28.3	6.791	2.724
B	Arrival S.F. #2	577820	21.1	5.809	2.402
F	Checkerboard	573850	23.6	5.880	2.164

Table 3 - Equivalent Wave Data

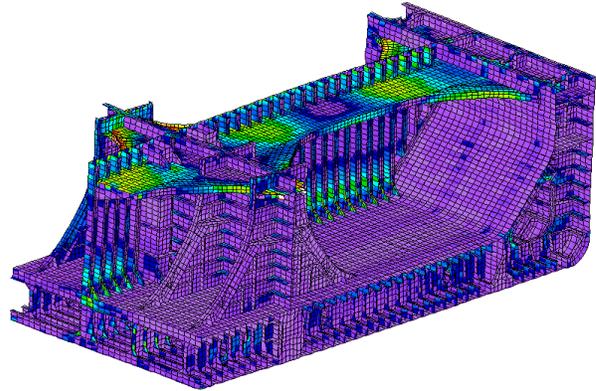| Case # | Load Case | DLP | Equivalent Wave | | | |
			Heading	Period (s)	Height (m)	Length (m)
14	125K Alaskan Crude	Moment	180	13.96	8.698	304.281
14	125K Alaskan Crude	Vert. Acc.	180	13.96	8.212	304.281
14	125K Alaskan Crude	Lateral Acc.	105	8.38	5.507	109.541
14	125K Alaskan Crude	Roll	75	15.71	7.718	385.106
27	Heavy Ballast	Moment	180	12.57	11.402	246.468
27	Heavy Ballast	Vert. Acc.	120	11.42	6.961	203.693
27	Heavy Ballast	Lateral Acc.	105	9.67	7.253	145.839
27	Heavy Ballast	Roll	90	13.96	7.069	304.281
B	Arrival S.F. #2	Moment	180	12.57	7.721	246.468
B	Arrival S.F. #2	Vert. Acc.	120	11.42	7.271	203.693
B	Arrival S.F. #2	Lateral Acc.	105	8.38	6.279	109.514
B	Arrival S.F. #2	Roll	75	15.71	8.215	385.106
F	Checkerboard	Moment	180	13.96	6.648	304.281
F	Checkerboard	Vert. Acc.	180	13.96	7.565	304.281
F	Checkerboard	Lateral Acc.	105	9.67	6.490	145.839
F	Checkerboard	Roll	105	15.71	8.851	385.106

4. *Development of numerous finite element models for the DLA analysis.*
   The models developed included:

- A 3-D stem-to-stern global model for overall DLA stress assessment (Figure 7).

- A 3-D intermediate model of the amidships structure.

- 3-D detailed general local model of the typical midship structure at frames.

- 3-D detailed general local model of the upper portion of a transverse bulkhead structure including the two stringers (Figure 9 and 11).

- 3-D detailed general local model of the lower portion of a transverse bulkhead (Figure 8).

- A 2-D refined mesh model of the aft centerline bulkhead between Frame 33 and 73 to examine high shear stresses observed in the 3-D global model (Figure 12).
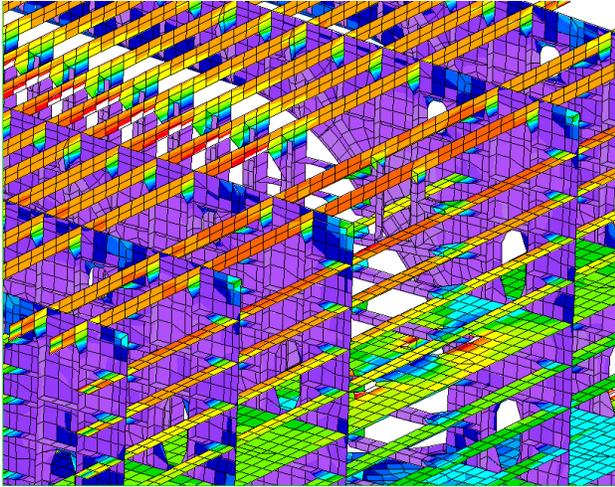
Scantlings were revised as necessary until all structure met the maximum allowable ABS Von Mises stress limit of 95% of yield. Note that since this analysis included detailed 3-D models of the complete midship structures, the general stress field was included in all typical structural components. For example, in addition to seeing the stresses in a 2-D web frame, the general stress levels in the frame brackets and the brackets to longitudinal connections were included. Another example would be the deck stresses; instead of looking only at the nominal deck plating stress the more detailed local models captured the additional stress increase created at the longitudinal-to-bracket connections at frames and bulkheads (Figure 9).
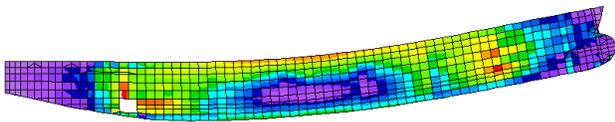

Fig. 8 General Local Model at Transverse Bulkhead

Appropriate judgment was used when evaluating the different stress levels. Judgement factors included consideration of element size, element shape and the modeling of structural discontinuities. Higher peak stresses are expected in a more detailed and finely meshed model. Hence stress results larger than 95% of yield were in some cases considered acceptable in finely meshed models. The structure was also analyzed for buckling without resulting in any significant changes. In all cases, the results were submitted to ABS for specific approval.

Fig. 9 Upper Shear Strake (Plating and Bulkhead Removed)

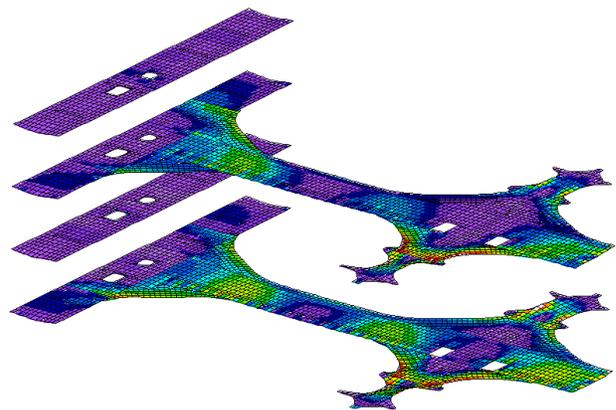**Fig. 10** Initial Centerline Bulkhead Design, Sag Wave

DLA Results

The following modifications were shown in the analysis to be effective and were implemented in the design:

- The centerline bulkhead thickness was increased at several locations. Initially large pump-room cutouts in the centerline bulkhead were reduced in size and modified in shape (Figure 10).

- The depth and thickness of forepeak frames and one forepeak stringer were increased.

- The thickness of the lower transverse bulkhead stringers was increased locally at the connection of the toes to the longitudinal wing bulkhead. This modification took place both forward and aft of the bulkheads. The panel stiffener arrangements were modified at both the upper and lower stringers.

- Two additional brackets were included between the vertical bulkhead stiffeners and the sloped hopper plating. The thickness was increased for all four brackets at this attachment.

- The vertical bulkhead stiffeners above the top stringer were modified, as was the attachment to the deck longitudinals. The depth of each stiffener slopes from 693 mm at the upper stringer to 280 mm at the deck longitudinal. The soft-toed bracket attaching the stiffener and the deck longitudinal was made smaller than the original design (Figure 6).

All DLA models were also rerun using element stresses instead of unaveraged nodal stresses, per ABS request. The results showed that all elements in the final global and intermediate models passed the 95%-of-yield criteria. The 3-D general local models showed a limited number of locations (elements) which did exceed the 95%-of-yield criteria. The upper most side shell girder and the double bottom girder exceeded the yield criteria in way of the access openings included in this model (Figure 9). Hull girder bending combined with the modeled cutouts stress concentration drives the stresses in these girders. The nominal stresses in the girders are in fact significantly lower than the nominal stress in the deck, which itself is significantly lower stressed than what is required by the ABS rules.
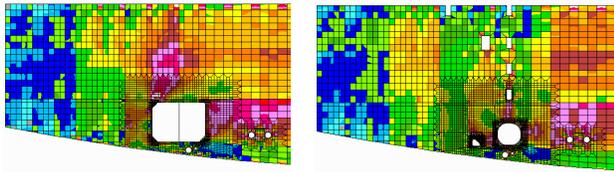
The Checkerboard load case combined with its corresponding maximum roll conditions created a maximum stress of 105% of yield in the triangular brackets at the base of the transverse bulkhead vertical stiffeners. The checkerboard loading pattern is not a typical condition and combining this in port leak-test condition with a long term extreme roll condition is conservative. The final design of this bracket had passed a detailed finite element analyses using solid elements and was subjected to both a still water checkerboard loading and an extensive fatigue analysis as described below.

Fig. 11 Horizontal Stringers, Checkerboard Loading, Bulkheads Removed

The same combination of checkerboard loading and long-term extreme roll created an above yield stress in

one element at the upper horizontal stringer (Figure 11). If such a combination of in port loading condition and extreme wave load were to occur it could lead to yielding of one localized region of the stringer. However, the remainder of the structure can absorb any load that may be shed. Since the normal loading conditions and cyclic loads create only low stresses at this location the design was deemed acceptable without further changes.

Fig. 12 Initial (r) and Final Pumproom (l) Opening Models

The 2-D model of the centerline bulkhead at the pump room showed above yield stresses at the fine meshed regions around the cutouts. These stress levels were deemed acceptable since they were induced by the fine mesh around cutouts rather than by the nominal stresses (Figure 12). Also, beam elements that were used in the 2-D model do not properly represent the beneficial effect of the flange coaming that is used as reinforcement around these cutouts.

No additional changes to the design were implemented nor required due to the evaluation of the element stresses. This is primarily a result of having used the more conservative unaveraged nodal stresses for the initial DLA submittal. Note that using the average nodal stresses, which is the default of many finite element packages and typically used by ABS for illustration purposes, is not a conservative approach. It will in many instances significantly reduce or hide high stress regions.

Importance of Model Test Program

A rigorous model test program was undertaken at SSPA in Gothenburg, Sweden prior to contract signing. As a result the development of a hull form was effectively complete when negotiations with the shipyard began. This proved advantageous as it allowed AMI and the Shipyard to immediately concentrate on structural design and resulting machinery arrangements. Foreseeing this benefit, during model tests, the seakeeping models were instrumented to later aid designers in correlating the DLA motions model to actual measurements. Comparison of the motions and extensive side shell pressure measurements has been documented in other publications [20].

Of note is that there was intent to determine if structural modifications were necessary based on results of a hydrodynamic model test program. The emphasis placed on redundancy in the overall design (e.g. the ship has two rudders, two propellers, two engine rooms etc.) demanded that relatively uncommon features were present in the hull form. For example, modifications were found necessary in the twin skeg arrangement that was chosen for the afterbody configuration. The area between the skegs was modified from a flat bottom to a V-shaped bottom to reduce aft slamming in following seas. Likewise, forepeak structure was later modified to accommodate resultant pressures found in the relatively flared areas of the bow structure.

FATIGUE ANALYSIS

Analytic Approach

The fatigue procedure used on the Millennium Class tankers has been developed by MCA in a continually evolving process that combines theory, finite element analysis techniques, and dynamic 3-dimensional load generation. The strength of the analytical process has been its consistent verification through actual field experience. Identifying, analyzing, and developing effective repairs for structures on a number of AMI's existing ships has successfully proved the fatigue procedure. The analytical process includes the following key steps:

1. Construction of global, intermediate, general local and local detail models capable of capturing and applying hull girder responses into small details such as rat-holes and bracket toes

2. Generation of dynamic 3-dimensional loads for a matrix of wavelengths, angles, and ship operating conditions using the *SPLASH* 3-dimensional CFD code

3. Analysis of the finite element models for the matrix of *SPLASH* loads to develop structural element RAO curves

4. Calculation of the fatigue crack initiation life of detail structures using the stress RAO's, anticipated ship voyage/weather data, and published S-N fatigue curves

Telescoping Finite Element Analysis

The Millennium Class tanker design was analyzed using a telescoping process that captures global and regional structural performance and applies it to the structural detail of interest. The process allows for

examination of details as small as rat-holes, lap-welded collars, and bracket toes.

The same Global, Intermediate and General Local finite element models used in the DLA analysis were also used in the fatigue analysis. In addition to the modified versions of six of the nine local models used in the initial design, three new local models were analyzed. These included bottom longitudinal to frame connections in hopper, deck longitudinals at frames and deck longitudinals at bulkheads.

These models are the final step in the telescoping finite element analysis process. They are constructed with general-local plate mesh along the boundaries, which is then transitioned to a mesh of greater density in the area of interest, using 8-noded brick (solid) elements with edge lengths as small as the plate thickness. Weld contours have been simulated using either 6-noded bricks or 8-noded bricks meshed along the weld contour to account for their geometric effect.

SPLASH-Generated Loads

The fatigue analysis used for this project is a fully three-dimensional dynamic spectral analysis. The load cases are generated using the three dimensional free-surface computational fluid dynamics code *SPLASH*.

Unsteady flows are treated in the frequency domain, as a linear small-disturbance, harmonically oscillating perturbation to the steady basis flow. First-order unsteady flow predictions yield unsteady ship forces and motions. Flow solutions are fully 3-D, with six degree-of-freedom ship motions, and arbitrary incident wave-heading angle. The unsteady flow is computed using a steady flow panel model with the hull and free-surface panels fixed, while movement is simulated via transfer of unsteady boundary conditions to the steady time-averaged panel location. Forces and moments are computed by integration of panel pressures over the vehicle surface, plus panel-based waterline integral contributions. The latter account for the oscillating area at the waterline due to ship and free-surface motions.

The *SPLASH* calculations were performed by South Bay Simulations, resulting in motions and pressure profiles for a matrix of waves. The hull was analyzed with nonlinear roll damping derived from Ship Motion Program (SMP) runs, at an average speed of 15 knots [24]. The analytical matrix (384 spectral fatigue load cases) included the following:

- Eight wavelengths, from 1/4 to 2 times the ship's length

- Seven wave-angles from ahead to astern in 30^0 increments. Since "windward" and "leeward" effects are not symmetric, off-centerline models required 12 wave angles (full 360^0)

- Two loading conditions - Full Load and Ballast

- The real and imaginary cyclic stress components (two instances in time are used to determine the complete cyclic variation, assuming sinusoidal loads and responses)

Spectral Fatigue Analysis

Fatigue can be divided into two stages: an initiation phase (calculated here using Miner's Rule) and a growth phase (calculated using fracture mechanics), until the crack reaches a critical length and propagates in a brittle mode. Crack propagation analysis was not completed for this effort, as the objective was to minimize or eliminate crack initiation [21]. The crack initiation phase is calculated in the following steps:

1. The finite element models are analyzed for every *SPLASH* run, starting with the global model and telescoping down to the detail local models. The hydrodynamic pressure fields are mapped onto the finite element models using a bi-linear interpolation program. The 6-DOF calculated accelerations are applied to the light ship weight, and are used to derive the fluctuating internal tank pressures. Once parent model analysis is complete, the boundary reaction forces are transferred to the telescoped model, and pressures and accelerations applied to the applicable contained elements.

2. The real and imaginary stress results are vector-added (square root of the sum of the squares) to calculate the cyclic stress component for a given load condition, wavelength, and heading. By analyzing the finite element models for all loading cases and normalizing to wave height, stress RAO's are developed for all free surfaces of every solid element in the detailed models.

3. The weather spectra, taken from a hindcast study based on historical hindcast weather data (Navy GSOWM) along zones in the TAPS trade route are combined with the stress RAO's to produce response spectra. This directional weather data combined with an assumed trip profile of travel between Valdez, Alaska and Cherry Point, Washington three times per month determined the weather spectra.

4. The response spectra are compared with published S-N curves to calculate Cumulative Damage Ratios (CDR's), an integrated ratio of the actual fatigue cycles at a given stress divided by the allowable number (defined by the S-N curves).

5. The CDR's are integrated across the ship voyage profiles to obtain a fatigue crack initiation prediction.

SN-Curves

A number of SN curves have been experimentally determined by the United Kingdom Department of Energy, and are used as an industry standard [25]. Curves such as F and F_2 apply to calculations based on nominal stress fields. Since the models are built and analyzed to the "hot-spot" detailed level, the appropriate curves are the 'C' and 'D' curves. The "C" curve is appropriate for parent plate. The "D" curve is more conservative and is used for elements adjacent to welds. It is possible to improve the fatigue performance at the weld toes, by reducing or putting in compression the intrusions or other imperfections, which is an inherent feature of weld toes in steel.

Edison Welding Institute's experience based on various test data, indicates that the fatigue life at the weld toes can be extended to approximately a "C" curve if burr grinding or hammer peening is used to form a smooth curved area which removes the toe and all undercut [26]. Hence, the fatigue life for these details can be assumed to increase by a factor of ~2.5, making "C" curve fatigue life prediction more appropriate than "D" curve prediction.
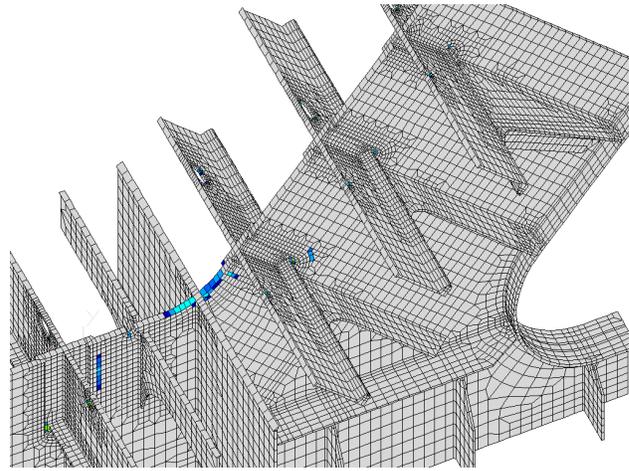
Fatigue Results

Modifications were necessary in most of the structural details in order to achieve the desired 30-year fatigue life. Most modifications were minor and included adjustments such as softening of bracket terminations, changing shape and location of erection joint cutouts, changing plate thickness and the use of full collars at a few locations.

More extensive improvements were needed in order to reach the desired fatigue initiation life in the lower hopper and at the deck longitudinal to vertical bulkhead stiffener connection. Even with the improvements implemented from the preliminary design analysis, further improvement were needed to extend the fatigue life in the radius tank top plating at web frames, and in the adjacent web frame cutouts.
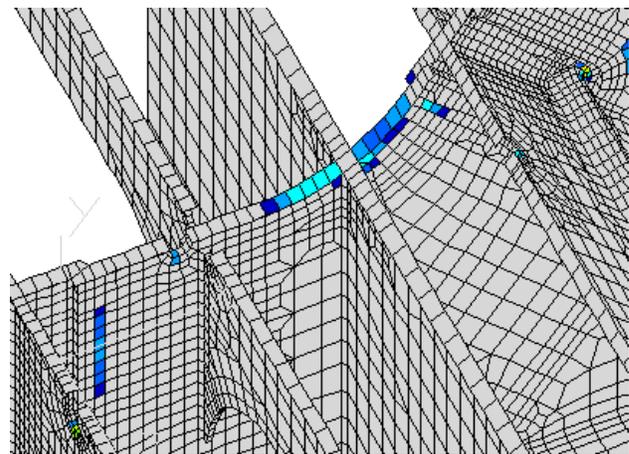
In the hopper connection, the desired fatigue life was reached by using a full collar in way of the adjacent longitudinals. A partial longitudinal stiffener was added between the last tank top longitudinal and the girder below the radius hopper. Finally, to ensure that the desired fatigue life was achieved, peening was used on the welds between the curved portion of the tank top plating and web frame (Figure 13 and 14).

A significant stress riser was found in the deck longitudinals where they intersected the vertical bulkhead stiffener. The initial design used a large vertical stiffener in combination with a large bracket at this connection; the final design, which gave us the desired fatigue life, used a tapered vertical bulkhead stiffener in combination with a small soft-toed bracket (Figure 15). The tapered vertical stiffener reduced the longitudinal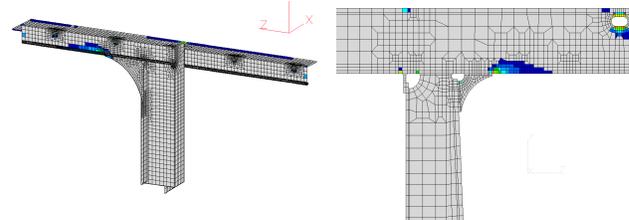 stiffness transition at the connection with the deck longitudinal while still having the needed stiffness at the upper horizontal stringer.

Fig. 13 Lower Hopper, Tanktop Plating Removed

Fig. 14 Lower Hopper, Zoom of Radius, Plating Removed

Fig. 15 Initial and Final Bulkhead Stiffener to Deck Longitudinal Connection

VIBRATIONS

The shipyard performed preliminary vibratory natural frequency studies on a subcontract basis with Det Norske Veritas (DNV). The studies were based upon a two-dimensional variable beam model for the hull-girder and a two-dimensional beam model with springs for the deckhouse. Simple beam and plating theories were used for the local structural elements.

The studies were performed to determine if there were any resonant frequencies with the 4th and 8th order of the propeller and/or 7th order of the main engine. The studies revealed that, in the after body, several local members and panels were deficient due to the reduced frequencies in the submerged mode (fluid one side or both sides). The corresponding inertia of these members and panels was increased to ensure that fatigue failures would not result from their vibratory response.

The preliminary studies also determined that there was a resonant condition of the deckhouse bridge wings with the propeller 4th order excitation frequency. Because the studies determined that there was a resonant condition with the bridge wings, additional studies were warranted to determine the forced response of the bridge wings with the interaction of the hull.

The final vibratory (natural and forced) responses were determined by a three-dimensional model of the entire vessel including the main engines, with the model consisting of 6,570 elements with 20,190 degrees of freedom. The calculated pressure impulse forces induced from the propeller as well as the imposed main engine forces were applied to the model, for the full load and ballast conditions.

The forced response study determined that the resulting vibratory response for the bridge wing was not in compliance with ISO standard velocity limit of 4.0 mm/sec for a frequency of 8.47 Hz, related to the susceptibility of human exposure. Hence, the vertical-truss support configuration for the wings was amended as well as the support structure between the bridge windows.

In the sloshing analysis, the first mode natural sloshing resonance period (with the vessel's pitching period) was determined to be at only 18% of the cargo tank filling height. This would result in the corresponding induced pressures being less than the normal required design pressures.

OVERVIEW OF SHIPYARD ACTIVITIES

Plan Review Process

The design review process resulted in a particularly interesting relationship between the Shipyard, AMI, and JJMA. AMI contracted with JJMA to support design review. Drawings were issued from the Shipyard to both AMI and JJMA. JJMA performed initial review of the drawings for compliance with the specification and regulatory body rule. Comments were provided to AMI in the form of detailed comments on the design. AMI in turn reviewed the comments, made appropriate changes as necessary based on Owner preference or experience and submitted the final review comments to the Shipyard. In order to ensure all issues were addressed, weekly meetings were held between AMI and the Shipyard to review design issues. The end result of this process yielded minimal on-site staff for AMI but included the overall expertise of a design firm with extensive design review experience.
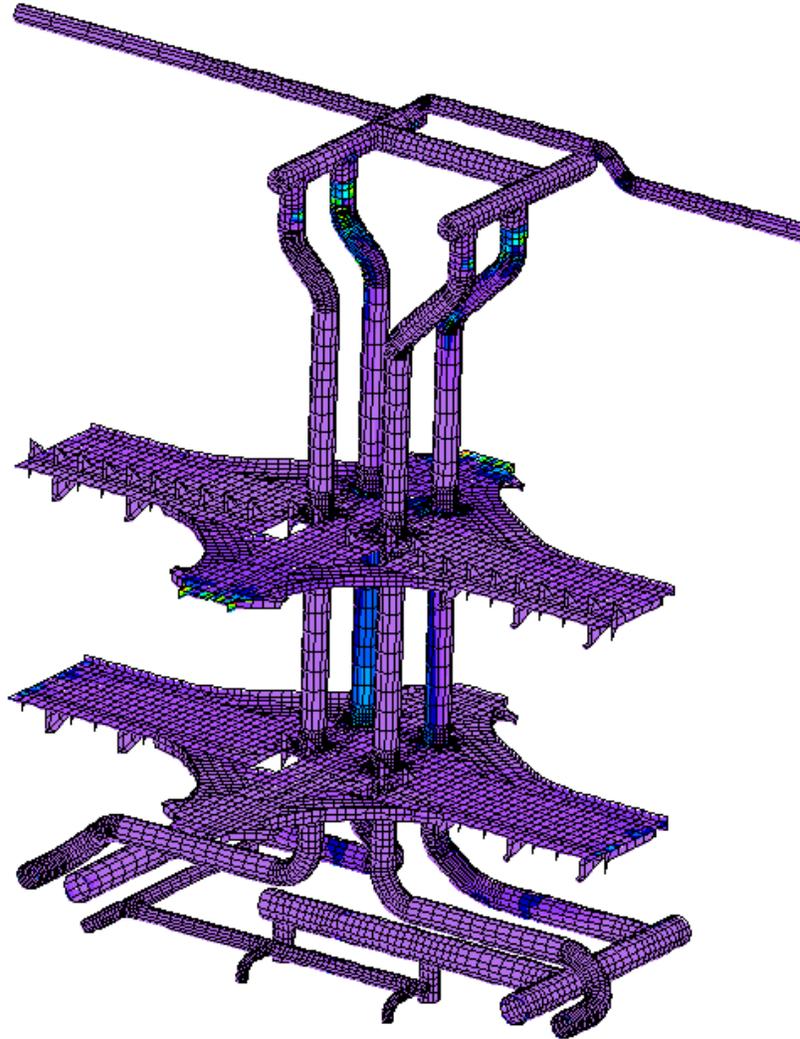
Construction Milestones

Keel laying for the *ARCO ENDEAVOUR* occurred on May 5, 1998 and the ship was launched on December 17, 1999. Keel laying for Hull 2498, the *ARCO RESOLUTION*, took place on July 12, 1999. Keel laying for the *ARCO DISCOVERY*, Hull 2499, is scheduled for November 2000.

Analysis in Support of Production

During the detailed design phase and into the construction period, several miscellaneous structural issues were also addressed through the use of finite element analysis during the design and building phase of the project:

- Rudder and Associated Castings - A rudder analysis was performed to verify the adequacy of the rudder design when subjected to hydrodynamic loading due to both ocean waves and ship's steering. Past experience with cracking at sharp radii at the lower gudgeon led to an expressed emphasis on the rudder design by AMI. Prudent design work by the Shipyard resulted in an acceptable design and utilized a continuous casting between the upper and lower gudgeon.

- Cargo Riser and Drop Pipes - An extensive analysis of the cargo riser and drop pipes in the cargo tanks was performed. The piping system was analyzed for internal thrust loads, cargo sloshing and loads induced by thermal expansion. In the desire to keep the exposed Upper Deck clear of oil carrying pipes to the greatest extent possible all cargo pipes were run through the cargo tanks. At the manifold the cargo fill and discharge lines run vertically from the innerbottom tank top to the Upper Deck and pass through the horizontal stringers. Initially, the riser and drop pipes were to be welded at their penetrations through the stringers. With the ambient steel temperature as low as 40 degrees F (4 degrees C) and the cargo loaded at as much as 105 degrees F (41 degrees C) there proved to be a significant thermal expansion in the pipes. The solution was to

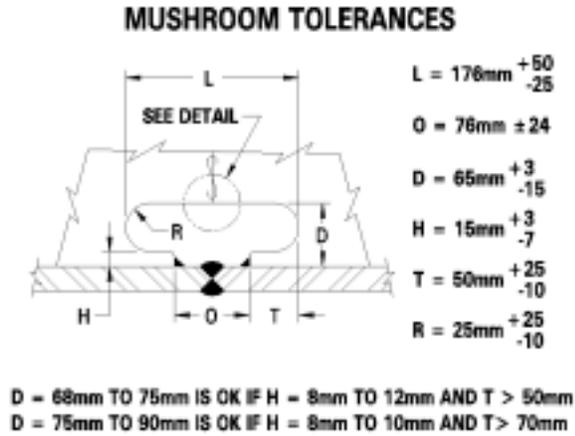**Fig. 16** Cargo Riser and Drop Pipe Model (Upper Deck Removed)

leave the cargo pipes loose through the stringers and anchor them to restrict horizontal motion, allowing vertical expansion. This eliminated "locking" the stringers together as well as pushing up the Upper Deck (Figure 16).

- Plug Unit Stresses - An analysis was also performed to identify the amount of locked in stresses created by fitting of the last of the construction block in each transverse band across the ship. These Upper Deck units were plugs placed between the centerline bulkhead and the longitudinal bulkhead structure. In matching of this plug unit with existing structure at the upper web frame erection joint it was found that the sequencing of weld-out on panel stiffeners was critical to maintaining the in-plane alignment of the web frame. The analysis demonstrated how certain

panel stiffeners could be freed-up to avoid any adverse effects of the weld-out process.

- Erection Joint Cutout Tolerance - The early finite element analyses proved to be a useful tool later in the construction process. This became apparent in the fabrication of "mushroom"-shaped cutouts that spanned erection joints. Because of minor variations in the amount of neat material on some units or the occasional shift in placement of longitudinals the dimensions of the mushroom cutouts varied. Because of prior knowledge that these mushroom cut details were sensitive to fatigue a design study was undertaken. The desire was not to analyze each detail but to provide a range of dimensional tolerances for the mushroom cutouts. Knowledge of the relative effects of variations in the mushroom

18

cutouts gave both Shipyard production personnel and AMI's steel inspectors a hard and fast guide for cutouts in question during the fabrication process (Figure 17).

MUSHROOM TOLERANCES

$$L = 176mm \, ^{+50}_{-25}$$
$$O = 76mm \pm 24$$
$$D = 65mm \, ^{+3}_{-15}$$
$$H = 15mm \, ^{+3}_{-7}$$
$$T = 50mm \, ^{+25}_{-10}$$
$$R = 25mm \, ^{+25}_{-10}$$

D = 68mm TO 75mm IS OK IF H = 8mm TO 12mm AND T > 50mm
D = 75mm TO 90mm IS OK IF H = 8mm TO 10mm AND T> 70mm

Fig. 17 Construction Tolerance for "Mushroom" Cutouts

- Weld Procedure for Bulb Plates **-** The desire by ARCO to use bulb plates provided another unique challenge for the Shipyard. With no previous construction experience using bulb plates there was a need to develop weld procedures and disseminate the information throughout production. Little was found in the way of published guidance relating to the end preparation for butted connection of bulb plates. The ARCO steel inspectors had significant international experience and worked with the Avondale welding engineers to perfect end preparation details suitable for use in production. Samples were fabricated in the Shipyard Welding Laboratory and an approved process was established. Buy-in was achieved between the Owner, the Shipyard and the Classification Society.

Stages of Construction/ Block Breakdown Photos

Appendix A provides photos taken during various construction phases of the Millennium Class tankers. The photos provide various perspectives on the structure and the structural details that are included on the vessels.

LESSONS LEARNED

The significant scope and unique approach on the Millennium Class Tanker project has offered many lessons to be learned. With the extensive analytical work that was performed and the feedback into the design it is safe to say that few, if any, aspects of the overall design

would be changed if the project were repeated. The greatest application of the lessons learned on the project can be used in the processes undertaken to meet design requirements. Important caveats were illustrated in the finding of unexpected analytical results and in the unique production challenges that this ship presents.

Encourage Extensive Development of Scantling Plan

One of the most important aspects of the design effort was the translation of the Scantling Plans into the design details. The Midship Section was clearly defined and the detailed design of the cargo block was fairly straightforward. However, when the detail design moved to the forward and aft transition structure, the challenge to achieve continuity was significantly increased. This occurred for a number of reasons. Scantling Plans were developed only to a preliminary extent. Instead, effort was made to quickly support the detailed structural needs of the DLA and fatigue analysis rather than to develop the detailed Scantling Plans. As detailed design progressed it became clear that additional development of the Scantling Plans at the early stages of design would have been beneficial. Most importantly, a full definition of the fore and aft structural transition areas should be clear at the scantling level.

Explore Local Details Carefully

Neither SafeHull nor DLA initially identified some problematic structural areas. It was particularly noteworthy that no stress or fatigue problem showed up at the lower hopper in either the SafeHull or the DLA analysis. No problems were identified at the side shell, bottom or deck longitudinal connections. Fatigue was addressed in SafeHull but SafeHull empirical tables predicted much longer life than what the detailed fatigue analysis revealed.

In other cases, findings from the DLA that were not addressed in SafeHull were also of significant interest. A prime example is the strengthening of centerline bulkhead away from midship, particularly in way of cutouts in the pump room. SafeHull and DLA are useful tools in design but it is also necessary to take care of local fatigue-sensitive details.

Know Your Design Software

The sensitivity of long-term extreme calculations was noted when comparing extreme values based on output from different ship motion programs. The DLA procedure provided significantly different long-term extreme results even when the basic motion characteristics of the input matched reasonably well with the input of the other ship motion programs. The extreme roll angle calculated by SMP, based on model test-derived damping coefficients, gave an unrealistically high long-term extreme roll angle. The *SCORES II* program, using a standard damping factor, estimated a maximum roll

angle consistent with what has typically been used on DLA analysis of similar ships.

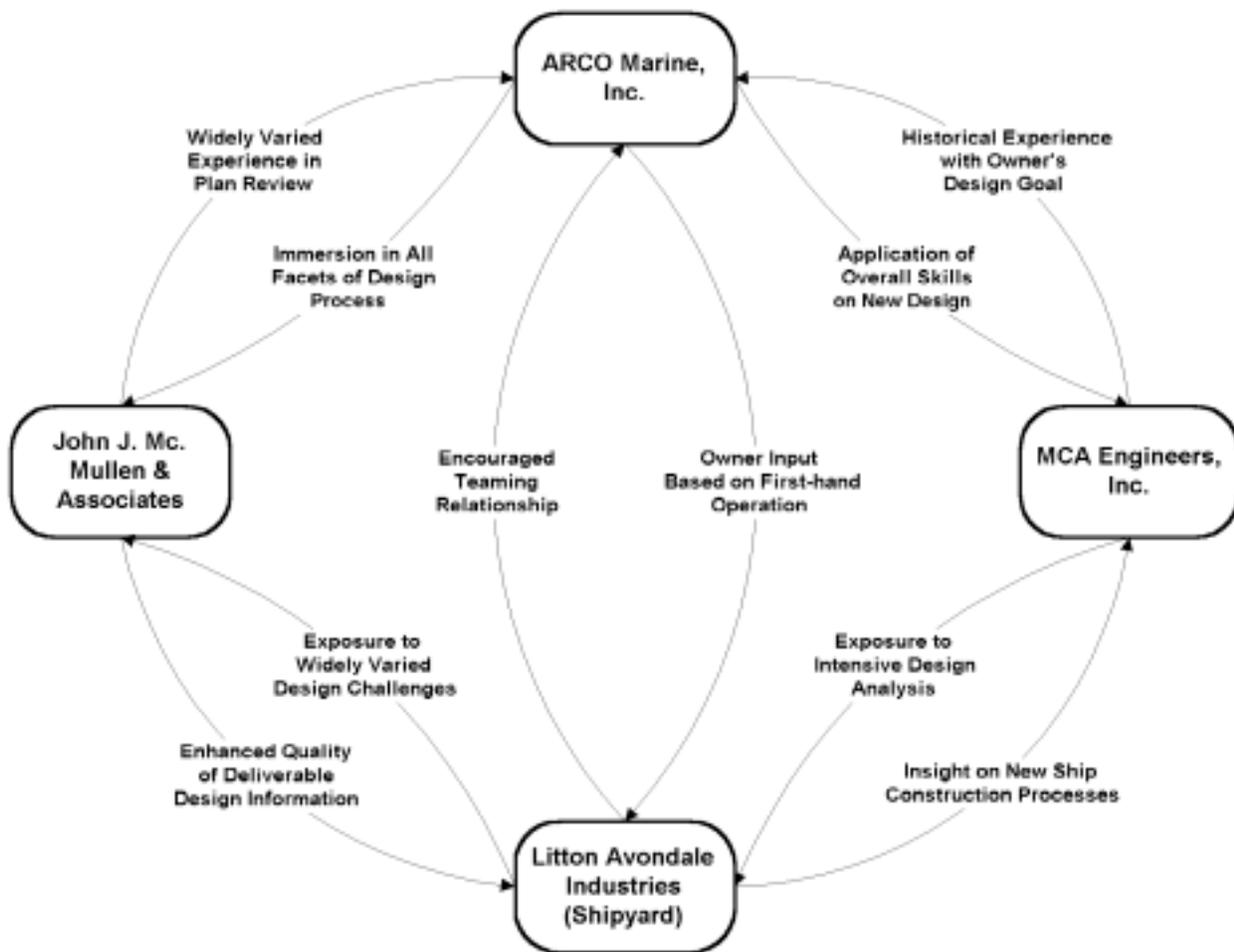**Understand Design Impact on Engineering and Production**

One particularly interesting aspect of the Millennium Class tanker design was the impact on engineering support services and Production. As a result of the effort to achieve continuity of structure the overall ratio of parts derived from plate versus parts derived from shapes was significantly different. That is, the exclusive use of backing brackets and web frame stiffeners cut from flat plate was not typical of other vessels. The Millennium Class tankers have a ratio of plate-originated parts to profile-originated parts of approximately 70:30. According to the Litton-Avondale Lofting Department this varies significantly from other vessel designs where the typical distribution is relatively standard at 50:50. This variation resulted in a redistribution of man-hours spent in the lofting effort as well as in the production loading of product lanes. In short, it was necessary to cut more parts cut on plate burning machines.

Take Advantage of a Team Approach

The team approach of addressing the structural design of the Millennium class tanker proved to be an excellent situation. Ideas were exchanged openly, fitness of the design was supported by extensive experience and the overall quality of the final product was enhanced. This carries not only to the ship itself but also to all design information that will be maintained throughout the life of the vessel.

Constant communication was necessary to make this approach work. In the end, the Owner obtained significant input on the design and the design requirements were met. The Shipyard benefited from the Owner's past experience and obtained information on new design techniques from the contractors. The consultants derived benefits from the Owner's extensive exploration of details and new design requirements.

Fig. 18 Diagram Showing Selected Benefits of Team Approach to Millennium Class Tanker Project

20

CONCLUSION

The effort to achieve a high structural standard for the Millenium Class tankers clearly departs from traditional thought processes. Design has been extended beyond Class Society requirements to incorporate lessons learned as successful marine operators. Throughout design the goal was to improve the safety and structural reliability of the vessels and address the needs of future operators of the ships. While the physical result of these effort are visible now, in the end, time will be the ultimate judge of success.

ACKNOWLEDGEMENTS

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DISCUSSIONS

Mr. Phil Rynn, Senior Staff Consultant, American Bureau of Shipping (ABS):

The paper is an excellent illustration of how a project requires the interface of all to achieve a structure that covers all facets for a successful ship. The owner, ARCO Marine, carefully selected a design team to achieve their aim of a ship that would meet the rigorous demands of their trade. The team selected had all the elements necessary for success: the operational experience of the owner; the design experience of John J. McMullen and Associates, Herbert Engineering, The Glosten Associates, and MCA Engineers; Litton-Avondale, the shipyard; and SSPA, the model test facility. MCA also provided FEM analysis abilities for the team. MCA's role was to assess the structure for failure based on stress distribution for the intended loading expected on the trade route from California to Alaska. Other important members of any team in a ship construction project are the flag of registry and the classification society. The United States Coast Guard rendered excellent support to the ARCO team early in the design. This was by advice on the latest requirements applicable to the vessel and through review of initial arrangements. ABS also participated to define the classification requirements as well as provide adequate guidance to MCA in the analysis of the design for compliance with DLA (Dynamic Loading Approach) and selection of details for Spectral Fatigue. This was to reduce duplication of effort in the scope of work performed by Litton-Avondale, MCA and ABS.

The team provides the innate abilities to meet the requirement defined by ARCO of " Safety, reliability, proven design, necessary fatigue life and maintainability."

Areas where the design could have made better use of printed literature are:

1. Stringer arrangement on the oil tight bulkhead recommended in Tanker Structure Cooperative Forum – use of 3 stringers versus 2 stringers selected. This is illustrated in figure 2.8 of the **Guidelines for the Inspection and Maintenance of Double Hull Tanker Structures.**

2. Web stiffener detail shown as figure D, Group O of structural details. This is in Appendix IV of the **Guidance Manual for Tanker Structures.** This was first published in 1997 and, therefore may not have been known by the team preparing the design.

3. Mushroom cutout at an erection joint should be avoided whenever possible. This detail is a known location of fatigue cracks. I believe ARCO has

operational experience and MCA has analyzed this detail in the past. This detail has been analyzed for fatigue and it seems that it has been employed in this design. This detail has specific fabrication requirements. Have the tolerances been easy to achieve? The author should advise on this. It is preferable to eliminate these as has been done in the drainage cuts.

4. Structural alignment of other structural members is not mentioned. What tolerances were applied to other areas and were these more or less restrictive than required for the mushroom cuts? It would be a benefit to others to know how the information, from the FEM (Finite element Method) design analysis, is provided to others involved in the fabrication of the structure. Also if it has been used when monitoring fabrication at the yard by Litton-Avondale and ARCO.

The paper mentions that SafeHull has been used in assessing the design. Did Litton –Avondale do the SafeHull analysis? SafeHull has developed the direct fatigue assessment in Phase A to cover longitudinal connections to webs and bulkheads. SafeHull requires other details to be assessed for fatigue. This would be done in Phase B where fine mesh 3D modeling is employed in the analysis to more closely define stress and fatigue. Discussions were held on analysis with class, owner, yard and MCA. Fatigue issues were discussed and deferred to subsequent analysis using DLA results. Therefore, it is clearer to state that some locations, where the design required improvement to meet the desired fatigue life assessment, were not known until completion of Spectral Fatigue. It should also be underscored that SafeHull has a target fatigue life of 20 years. The design fatigue life for the Millennium Class Tanker is in excess of 20 years and actually 30 years as specified by ARCO.

I have expressed my personal views and not those of ABS. I thank the authors for an informative paper that illustrates for the industry the benefits of proper teaming, analysis and implementation of the findings in the final structure of the ship. May the ENDEAVOR and the sisters have many years of successful service for the operators and those who sail on her.
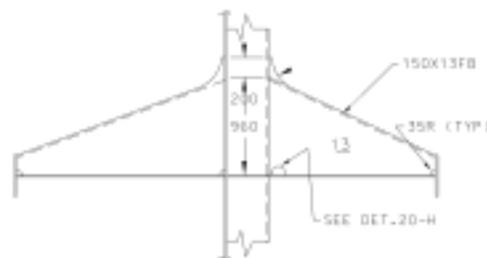
Authors' Response:
The kind words presented by Mr. Rynn are greatly appreciated. Undoubtedly ARCO Marine, now Polar Tankers, Inc., received great benefit from a close working relationship with the team directly responsible for design and construction of the vessel. This team did indeed extend one step further, and it is important to point out that the design team as a whole received significant guidance from ABS throughout the project.

Within the structural context of this paper ABS provided important guidance throughout the design and construction process. This assistance began with early consultation on structural arrangements and, as noted, classification requirements. As design activities progressed, it was vital that ABS participated in oversight of the analytic efforts. Periodic meetings were held to review progress on the SafeHull, DLA and Spectral Fatigue analyses. Such "benchmarking" during the design progression served as a sounding board for design improvements and added greatly to the fitness of the design.
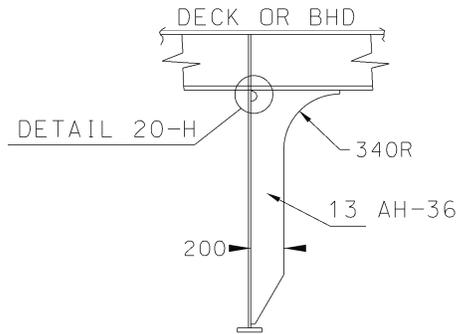
Litton-Avondale did perform and complete both Phase A and Phase B of the SafeHull analysis. In order to accommodate the desired 30-year fatigue life of the Millennium tankers the upper limit of the Fr/PS ratio was modified to a maximum of 0.73 (as defined in Section 5/2AA.3.3.1 of ABS Rules). True to the above discussion, ABS played an integral role in steering the work content of the SafeHull analysis so as to avoid duplication of work in the later Spectral Fatigue analysis.

ARCO did seek to make significant use of printed literature. There were some cases, however, where unique features of the design excluded use of specific reference material. The first example presented is the two stringer arrangement on the oil tight bulkheads. The hopper configuration and the spacing of longitudinal stringers in the double sides were the primary drivers in selection of this arrangement. Early in design it was determined that use of a three stringer arrangement would have created a problematic connection at the upper hopper and resulted in undesirable access arrangements in the wing ballast tanks. This can be seen by comparison of Figure 3 with Figure 6 in the paper. While the current design meets all structural requirements, it is true that further exploration of the hopper and wing tank stringer arrangements and accommodation of a three stringer design may have yielded undiscovered benefits.
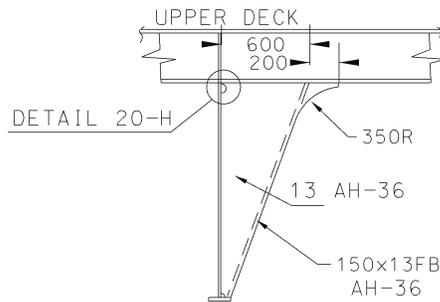
The web stiffener detail from the **Guidance Manual for Tanker Structures** was used extensively throughout the design. Details from the Midship Section are provided in Figures D1 through D4. It should be noted that this "soft heel" connection was, in applications particularly sensitive to fatigue, less effective that a soft toe stiffener with a soft toe backing bracket.
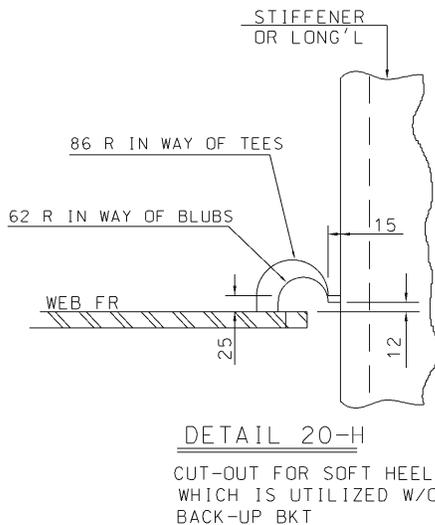
Fig. D1 "Soft Heel" Tripping Brackets on Centerline Vertical Web Frames

Fig. D2 "Soft Heel" Web Stiffener on Upper Deck Transverse Web Frames or Centerline Vertical Web Frames

Fig. D3 Tripping Bracket on Upper Deck Web Frame

DETAIL 20-H

CUT-OUT FOR SOFT HEEL WHICH IS UTILIZED W/O BACK-UP BKT

Fig. D4 Detail of "Soft Heel" Cutouts for Bulb Plate and Tee Stiffeners

Use of mushroom cutouts was evaluated carefully and extensively in preliminary design and in the Spectral Fatigue analysis. It should be noted that this analysis used the same methodology that has accurately predicted, on current single hull ships, the actual fatigue life of mushroom cuts in the bottom shell. The inherent hull girder features of the double hull vessel did allow use of the mushroom cut details at the innerbottom and bottom shell. The lower neutral axis in the hull girder effectively results in lower stresses at these locations. Conversely, mushroom cuts did not prove feasible for use at the Upper Deck. To reduce the possibility of production induced notches at the weld toes the end wraps in the mushroom cuts were ground to a smooth profile at the shell plate.

The development of design tolerances for the mushroom cuts has been very successful. Tolerances have been easier to achieve as the production of the three ships moves forward and the learning curve takes effect. One further reason for development of tolerances and the decision to make use of mushroom cuts is that the bottom and innerbottom longitudinals are deflanged I-beams. The resulting T-beam web as welded to the plating cannot accommodate the use of collars at erection joints because of material remaining from the deflanging process.

The issue of structural alignment was not addressed in the paper. The standard Avondale alignment criteria for opposing structure is "thickness upon three" (t/2) in all areas. This guidance arises from ASTM standards. ABS, following review of the DLA analysis, identified three general areas within the ship where a "thickness upon two" (t/3) alignment criteria was to be held. This higher tolerance is in line with IACS standards.

The first area where the t/3 guidance was applied was in the alignment of the oil tight bulkhead horizontal stiffener to the double side horizontal girder at 9840 and 17120 mm above base line. A second area where the t/3 guidance was necessary was in the alignment of the vertical bulkhead stiffeners to the upper deck longitudinal members. The third area requiring t/3 alignment was at the toes of the upper deck and centerline web frames where they opposed the web frames in the ballast tanks. These alignments can be seen at the upper outboard and lower inboard areas of each cargo tank in Figure 3 of the paper.

Finally, it should be stated that the ARCO steel inspectors worked in concert with the ABS surveyors to ensure that all structure met the requirement of both the Owner and ABS. Copies of all structural analysis reports were made available and discussed with the inspectors prior to the start of fabrication. The resultant collaborative inspection effort in the fabrication and erection areas has ensured that the structure is of the highest possible quality. ARCO, ABS and the Shipyard's

Quality Assurance department carefully monitored structural alignments, weld details and performed non-destructive testing wherever necessary.

At the risk of leaving important players in the structural development of the ships unmentioned, the engineering efforts of Phil Rynn, Michael Johnson, Charles Dunlap, Gabriel Tam, Dan Cronin and Ernie Kotte at ABS Houston have been greatly appreciated. The surveying efforts of Jim Ghegan, Paul Hayward and Grant Gooding from the ABS office in New Orleans have been invaluable to the project. Overall, Polar Tankers would like to thank ABS for it's continuing role and oversight in the evolution of the Millennium Class tankers.

Messrs. H. Paul Cojeen and Jaideep Sirkar,

U.S. Coast Guard (*) HQ, Washington, D.C.:

We take great pleasure in being asked to comment on this outstanding paper, having visited the Endeavour this last December at the Avondale facility of Litton-Avondale Industries.

We compliment ARCO with starting with the right philosophy: do it right and do it thoroughly. They have clearly established that this new series of tankers is a corporate asset, and they have approached it accordingly. Some examples:

Redundancy – Though this paper has not concentrated on this the ship data and figures showing the independent, completely separate engine rooms. Their separation is complete: keel to the top of the stack, watertight and fireproof bulkhead. The two engine rooms are operated as separate entities in all phases of the voyage. Twin screw, slow speed MAN B&W engines driving Kamewa controllable pitch propellers, each with a shaft PTO. In addition to the PTO, each engine room has a power converter unit (PCU) and diesel generators, along with the corresponding switchboards. From the control aspect each engine room is designed as an independent space, with dual control rooms. The maneuverability of the Millennium class is equally designed for redundancy, with the tanker capable of operation with a single propeller at zero pitch and rudder hard over.

Greenliness - Again, this paper has not highlighted these aspects but referring to figures 16 and 17 tell the story. The cargo lines all go through the cargo tanks and only just come to the deck as risers at the manifolds. Thus, keeping leakage and spillage from the ship's cargo systems to the minimum.

Fatigue and details - No need to say very much, as the authors have given us the "instruction book" for design. They have shared many lessons learned. It is very rewarding to see the use of the words "critical areas".

Not so long ago - about the time the world's VLCC and the TAPS communities were becoming aware of the short fatigue life of longitudinal connections with the web at the side shell - those words were only spoken softly. How refreshing that all of the industry now addresses these issues in an open forum. We note also that the authors have told us in a uncertain terms that the wave environment in the Gulf of Alaska is about the most severe in the world. Note also the authors' added care in details - mushroom cut-outs for erection butts and the use of hammer peening technique to dress the fillets.

Steels and special shapes - It is gratifying to see the cooperative approach among the team. The higher portions of mild steel - versus the foreign shipbuilders nearly exclusive use of HTS - has surely been partly due to this sharing of ownership of the product. Look at figures A6 and 13; see the bulb plate!

I close with a request. Can you just imagine what the original color versions of figures 5, 8, 9 and 13-15 looked like? Since we are now moving to electronic versions of papers and technical publications, try and think of ways that color can enhance the communications. Seriously, the Electronic Media Committee is taking all these issues in hand and welcomes the experimenting and innovating of authors in producing papers FOR ELECTRONIC venues. Mr. Read tells me he will re-introduce the color presentations on the CD-ROM version.

Thanks again authors for the outstanding presentation, and ARCO Marine for what should be a super, environmental-aware ship for the next 30 years.

* The views expressed here are those of the discussors, and not necessarily those of the U.S. Coast Guard or the Department of Transportation.

Authors' Response:

Thank you to Messrs. Cojeen and Sirkar for their generous comments. It is flattering that the efforts of the design team have been so recognized. Indeed the design philosophy adopted early in the project has yielded a vessel that will be of great value to the Owner. Most importantly the project has been a tremendous learning experience for all groups that have been involved.

Regrettably, the details of the mechanical redundancy on the Millennium Class tankers did not fall within the scope of the paper. It should be noted however that Reference 12 from the paper does discuss the redundancy of the vessel at length and is highly recommended for those interested in the mechanical aspects of the vessel.

The discussion regarding "critical areas" does reiterate an important lesson learned from the project. As an industry and as engineers, we must become very familiar with the environment in which our vessels

operate. In the paper this is discussed in the context of designing to meet a desired fatigue life in a very severe environment. The same understanding of design requirements can be carried to high speed ferries, naval vessels, etc. Lessons learned and case studies should continue to be shared within the industry for the benefit of all. The authors hope that this paper and the experiences shared within are of benefit to those undertaking future shipbuilding projects.

APPENDIX

Fig. A1 View Looking Aft Along Transverse Web Frames in Cargo Tank

Fig. A2 Detail of Transverse Web Frame Toe Attachment to Tank Top

Fig. A3 View Looking Aft Along Hopper To Transverse Bulkhead

Fig. A4 Typical "Mushroom" Cutout at Erection Joint in Ballast Tanks

Fig. A5 View of Hopper After Erection, Looking Aft

Fig. A6 Detailed View of Hopper Connection, Looking from Below with Forward Unit Removed

Fig. A7 Photo from Bow Looking Aft

Fig. A8 Photo from Stern Looking Forward (Note Twin Skeg Arrangement Aft)