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Condition Assessment of Main Structural Members of Steam Schooner WAPAMA

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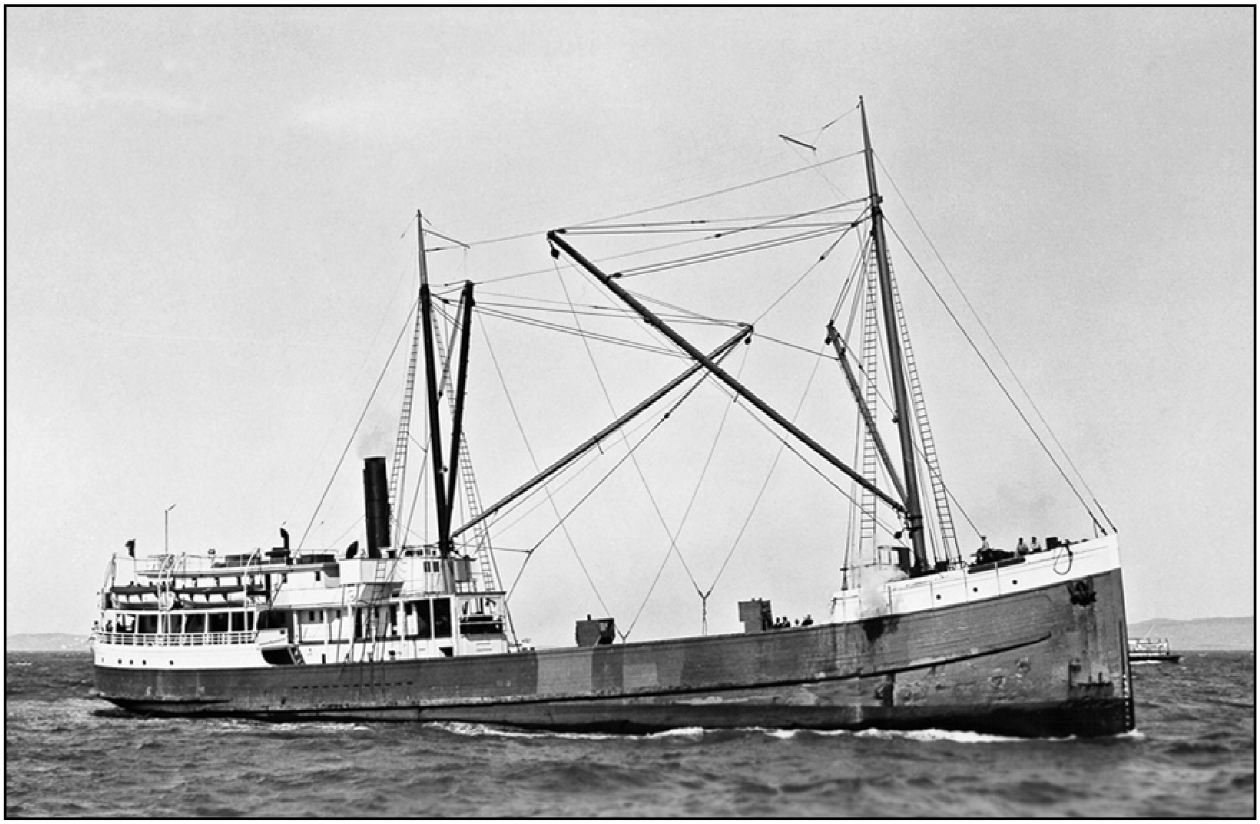

Abstract

The historic American ship WAPAMA is the last surviving example of the wooden steam-powered schooners designed for the 19th- and 20th-century Pacific Coast lumber trade and coastal service. Since its launching in 1915, the WAPAMA has had a long and productive life in plying cargo and passengers along the stormy West Coast from Mexico to Alaska. As the sole survivor of the once numerous class, the WAPAMA was declared a National Historic Landmark in 1984.

The wood structure of the WAPAMA has significantly deteriorated over the years and currently resides on a barge with internal and external structural supports. Portions of the vessel are unsafe for public access. Assisting in an effort to stabilize and rehabilitate this historic vessel, we conducted a field investigation on the current physical condition of the wooden structural members in January 2006. A variety of nondestructive testing (NDT) methods were employed to locate problem areas and define the severity of deterioration on key structural members such as keelsons, keel, ceiling planking, hull frames, clamps, and main deck beams. This report presents the main findings from this field investigation and demonstrates the use of state-of-the-art NDT technologies in evaluating physical and biological conditions of historic wood structures.

Keywords: inspection, ship, nondestructive, schooner, wooden hull, steam powered, rehabilitation

To convert from	To	Multiply by
inches (in.)	mm	25.40
feet (ft)	m	0.3048
gross tonnage (GT)	m^3	2.832

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Acknowledgments

Partial funding for this project was provided by the National Park Service and the San Francisco Maritime National Historic Park. Additional guidance was provided by Architectural Resources Group (San Francisco, California) and Allen C. Rawl, Inc. (Bradshaw, Maryland).

We thank Crystal Pilon, former General Engineer, Forest Products Laboratory, for assistance with field work and data analysis. We greatly appreciate the effort of Steve Schmieding, Technical Photographer, Forest Products Laboratory, for documenting the condition of the WAPAMA and assisting in the inspection process during this on-site investigation.

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Introduction

The vessel WAPAMA was built in 1915 and is the last surviving example afloat of some 225 steam schooners specifically designed for use in the 19th- and 20th-century Pacific Coast lumber trade and coastal service (Tri-Coastal Marine, Inc. 1986). These vessels formed the backbone of maritime trade and commerce on the west coast, ferrying lumber, general cargo, and passengers to and from urban centers and smaller coastal settlements. Those who built them took advantage of plentiful timber and built these ships out of wood long after builders in most of the western world had shifted to iron and steel construction. These wooden ships were a mainstay of the coastwise carrying trade for decades. As the sole survivor of the once numerous class, the WAPAMA was declared a National Historic Landmark in 1984 due to its international, national, and regional significance.

The WAPAMA is built almost entirely of old-growth Douglas-fir timber and is approximately 217 ft long and 50 ft from keel to house top, with a gross tonnage (or internal volume) of 945 GT. The construction is unique in its use of sister frames and lack of steel strapping. The hull is single decked and characterized by a plumb stem, full bows, straight keel, moderate deadrise, and an easy turn of bilge (Fig. 1).

In 1979, the vessel was removed from its berth at the California State Historical Maritime Park at Hyde Street Pier and moved to a submarine pen at Hunter Point Naval Shipyard. This move to quiet water was to minimize stress on the hull. Prior to building a breakwater in the mid-1980s, the Hyde Street Pier resembled an ocean pier more than a bay pier. Winter storms, in particular, were extremely stressful on the entire fleet.

In 1980, the vessel could no longer remain afloat due to severe deterioration and was hauled out of water and placed on Barge 214, berthed at Pacific Drydock Co., Alameda. Since that time, the WAPAMA has remained on the barge and received limited maintenance. Currently, the vessel resides on Barge 214 in a flooded graving dock at the Richmond Reserve Shipyard in Richmond, California, and is unsafe for public access (Fig. 2).

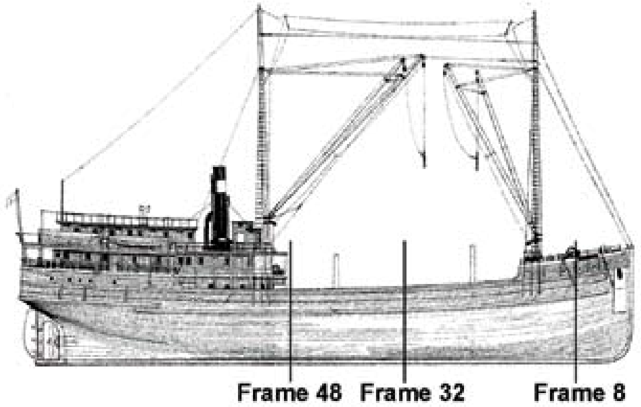

Figure 1. Starboard elevation of the WAPAMA.

Figure 2. A recent photo of the WAPAMA placed on Barge 214 at Richmond Reserve Shipyard in Richmond, California.

In an effort to stabilize and rehabilitate the vessel, the National Park Service tasked the Architectural Resources Group (ARG), an architectural firm based in San Francisco, California, to undertake a condition assessment of the vessel and provide preservation recommendations.

Scope of Work

In response to a request from ARG, the Natural Resources Research Institute (NRRI) at University of Minnesota

Duluth and the U.S. Forest Service, Forest Products Laboratory, signed a cooperative research agreement with ARG for conducting an on-site condition assessment of key wooden structural members of the vessel. This work was aimed at assisting a structural engineering analysis process to determine the possibility of stabilizing and rehabilitating the vessel.

In a recent condition survey of the vessel and barge, BMT Designers & Planners, Inc. (2005), provided visual assessment in terms of safety and stability of the vessel and conducted a preliminary structural analysis of the vessel's main features and support structures. The intent of our on-site investigation was to physically test key wooden structural elements that were deemed to be in critical or unknown condition and provide scientific evidence of WAPAMA's deterioration.

On January 10, 2006, the first day on WAPAMA, our inspection team met with several personnel involved in the preservation project: Gee Hechscher (Structural Engineer, Architectural Resources Group), Steve Hyman (Historic Preservation Specialist, San Francisco Maritime National Historic Park, National Park Service), Allen C. Rawl (President, Allen C. Rawl, Inc.), Trung-Son T. Nguyen (Architect, Pacific Great Basin Support Office, Facility Management Team, National Park Service), and Michael R. Bell (San Francisco Maritime National Historic Park, National Park Service).

This meeting resulted in focusing our NDE inspection on the key strength members. With the input from Steve Hyman and Allen Rawl, we identified the following features as priority targets for a four-day on-site inspection:

- Keelsons
- Assistant keelsons
- Keel
- Ceiling planks
- Hull frames
- Clamps
- Main deck beams
- Main deck stringers
- Waterways
- Hanging knees
- Pointers
- Main supporting columns

Inspection Methodology

The general physical condition of the WAPAMA had been assessed and monitored at periodic intervals since the acquisition of the vessel by the State Maritime Historical Park in 1957. Inspections in previous surveys and studies were mostly by visual observation and wood borings. In-depth information on deterioration levels of structure elements was limited. The focus of our investigation was to nondestructively determine the internal physical condition of key structural elements of the vessel that are usually difficult to assess by visual inspection. Two state-of-the-art nondestructive evaluation methods were employed in our investigation: (1) stress wave transmission technique and (2) micro-drilling resistance technique.

Stress Wave Transmission Technique

Stress wave transmission technique has been successfully used in decay detection in a variety of wood structures (Forest Products Laboratory 2000). The concept is that stress wave propagation is sensitive to the presence of degradation in wood. In general terms, a stress wave travels faster through sound and high-quality wood than it does through deteriorated or low-quality wood. The time-of-flight (or transmission time) of the stress wave is typically used as a predictor of physical conditions inside the wood. By measuring time-of-flight of a stress wave through a wood member perpendicular to grain, the internal condition of the member can be determined. Detailed information on the principles of stress wave transmission technique and guidelines for use and interpretation are given in *Stress wave timing nondestructive evaluation tools for inspecting historic structures—A guide for use and interpretation* (Forest Products Laboratory 2000).

Micro-Drilling Resistance Technique

The micro-drilling resistance technique is being used increasingly in the field to characterize wood properties and detect abnormal physical conditions in structural timbers. The micro-drilling resistance tool is a mechanical drill system that measures the relative resistance (drilling torque) of the material as a rotating drill bit is driven into the wood at a constant speed. It produces a chart showing the relative resistance profile for each drill path. Because it can reveal the relative density change along the drill path, it is typically used to diagnose the internal condition of structural timbers.

Drill resistance R_D (in Nm s/rad) is defined as

$$R_D = T/\omega$$

where T is drilling torque (Nm) and ω is angular speed (rad/s).

A micro-drilling resistance tool typically consists of a power drill unit, a small-diameter drill bit, a paper chart recorder, and an electronic device that can be connected to the serial interface input of any standard personal computer. The diameter of the drill bit is typically 2 to 5 mm, so any weakening effect of the drill hole on the wood cross section is negligible.

Inspection Procedure

General Procedure

On-site inspection of the WAPAMA was conducted by the inspection team between January 10 and 13, 2006, using the following general procedure:

- Identify critical areas and key structural elements (sampling)
- Examine moisture content (moisture meter)
- Perform stress wave scanning tests in key strength members (Fakopp Microsecond Timer, FAKOPP Enterprise, Agfalva, Hungary)
- Perform micro-drilling resistance tests on key strength members (Resistograph IML-RESI F400, IML, Inc., Kennesaw, Georgia)
- Document photographically the inspection process and ship conditions

Stress wave scanning and micro-drilling resistance were the two primary means used to determine the internal physical conditions of wood members.

Stress Wave Scanning

Stress wave transmission testing requires access to two opposite sides of a timber for attaching sensor probes. Therefore, stress wave scanning in the WAPAMA was conducted only on structural members that have both sides exposed and are within reach of the inspectors. Such members included keelsons, keel, stringers, main deck beams, vertical supporting members, pointers, and hanging knees. Stress wave transmission tests were performed on these members using a Fakopp Microsecond Timer.

For longitudinal strength members such as keelsons, assistant keelsons, keel, and main deck stringers, stress wave transmission tests (perpendicular to grain) were conducted along one, two, or three lines on the side surface. Intervals between two scanning points in the longitudinal direction varied for different members: 2.5 ft for keelsons and 5 to 6 ft for keel and main deck stringers. Figure 3 shows a typical scanning diagram for inspecting and mapping longitudinal members with stress wave transmission times.

For vertical supporting members, pointers, main deck beams, and hanging knees, stress wave transmission tests were conducted as a spot check due to the limited available time on the ship.

Micro-Drilling Resistance Test

Micro-drilling resistance tests were conducted to obtain relative resistance profiles for the key structure elements. The purpose of conducting micro-drilling tests was two-fold: (1) to confirm and determine the extent of decay in critical locations or areas that had been identified by stress wave scanning and (2) to determine internal conditions of key structure elements that cannot be scanned using stress wave transmission techniques.

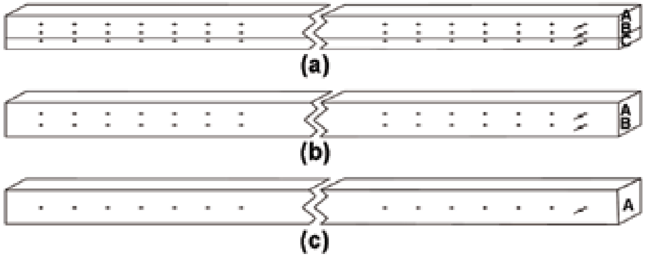

Figure 3. Scanning diagram of longitudinal strength members: (a) keelsons; (b) keel; (c) main deck stringer.

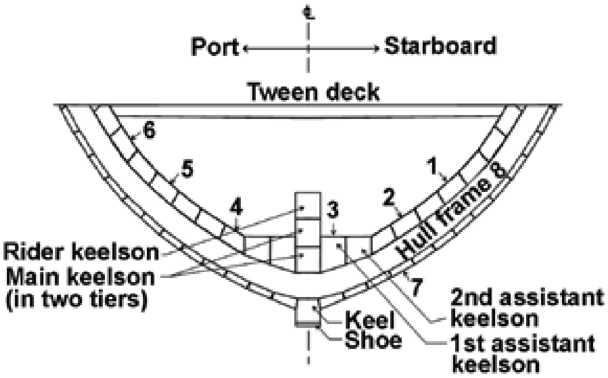

Figure 4. Schematic of drilling locations for the cross section at frame 8.

The drill was oriented so that its drilling path was perpendicular to the exposed face of the wood members. During each drill test, relative resistance was recorded on a wax paper graph and also stored in an electronic unit. Each resistance chart was properly coded to track its drilling location in a specific member. After testing, the electronic files were transmitted to a computer for further analysis. The maximum drilling depth of the tool we used is 15 in., so the internal condition of wood beyond this depth cannot be revealed.

Ceiling planks, assistant keelsons, hull frames, clamps, waterways, bulwark, and assistant stringers are the key strength members that cannot be evaluated with stress wave transmission techniques. To assess the physical conditions of these members, we selected three main sections along the length of the vessel for detailed inspection with the micro-drilling resistance tool (Fig. 1): (1) section at frame 8; (2) section at frame 32; and (3) section at frame 48. The drilling locations at these sections are illustrated in Figures 4 to 6.

To assist the on-site inspection efforts, we took a series of photographs and short videos to document the inspection process and the physical conditions of the key structure features. Example photographs are shown in Appendix A.

Main Findings

A summary of key findings follows. Photographic documentation and comprehensive NDE data tables are in the Appendixes.

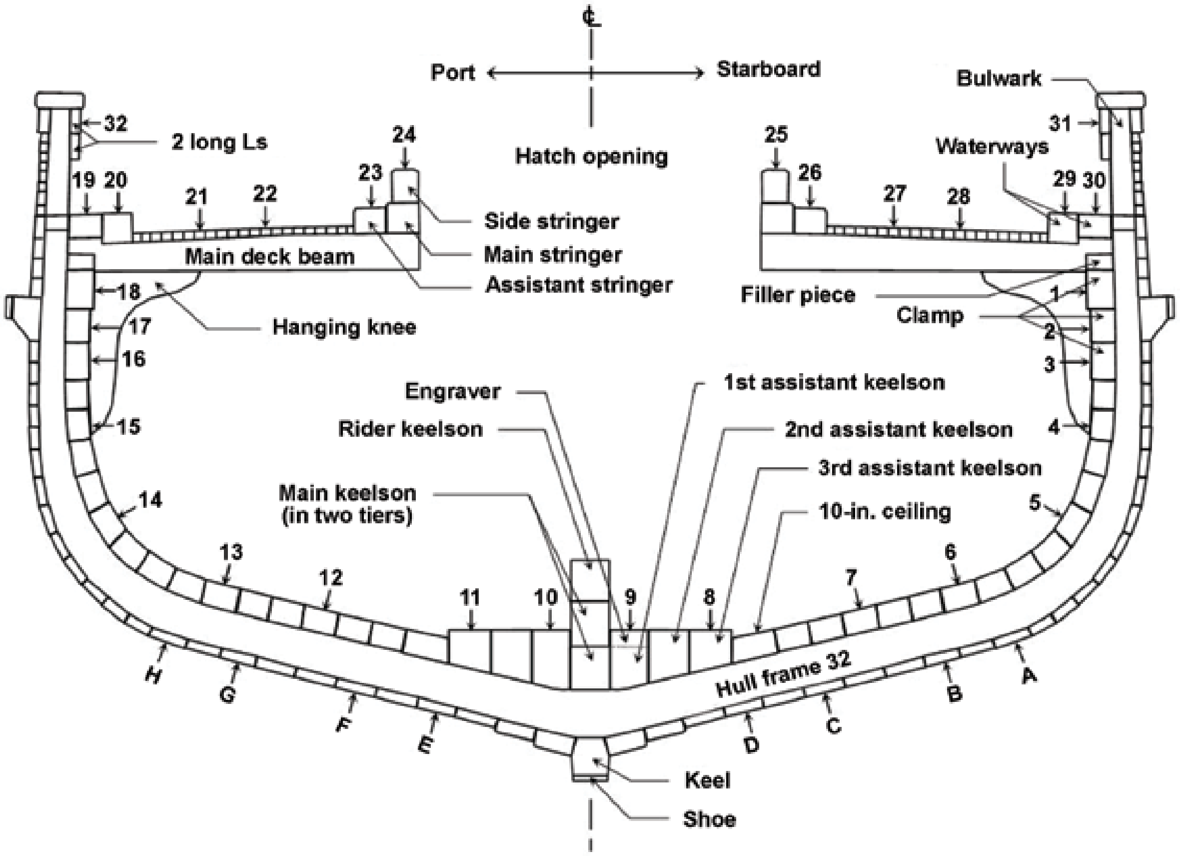

Figure 5. Schematic of drilling locations for the cross section at frame 32.

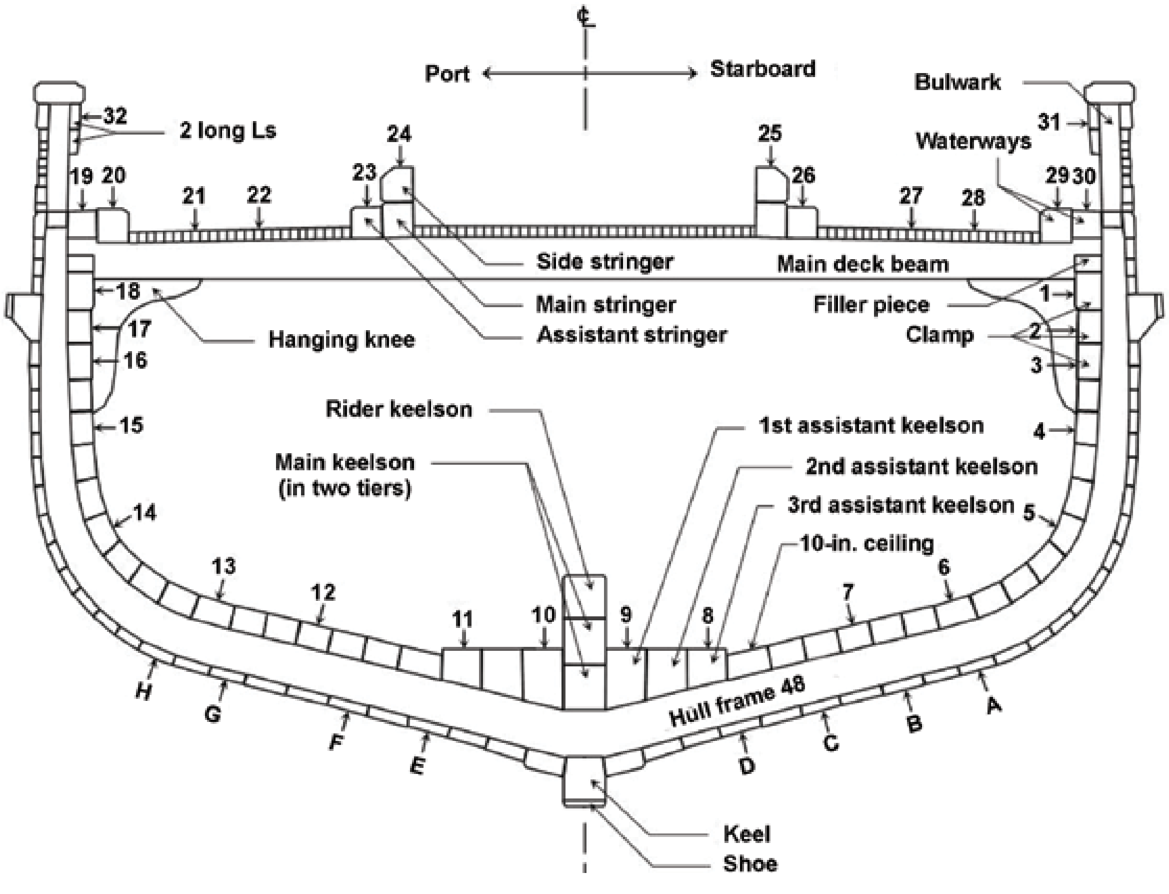

Figure 6. Schematic of drilling locations for the cross section at frame 48.

Keelsons

Keelsons are key longitudinal strength members and form the main backbone of the vessel. The keelson members in the WAPAMA include rider keelson (20 by 17.5 in.), main keelson (20 by 37 in. in two tiers), and three assistant keelsons, port and starboard.

The rider keelson and part of the main keelson (upper portion) are exposed above the top surface of the assistant keelsons and therefore are readily available for stress wave scanning. The assistant keelsons, on the other hand, only have the top face exposed. Therefore, the internal condition of the assistant keelsons can be evaluated only through micro-drilling tests.

Rider Keelson and Main Keelson

The rider keelson and main keelson (above the top surface of the assistant keelsons) in the cargo hold were stress wave scanned along three lines (Fig. 3a). Lines A and B were on the rider keelson, and line C was on the main keelson. The portion of the keelsons tested is between frames 7 and 48. The keelsons beyond this portion were not tested due to lack of access or difficult access.

Figure 7 illustrates the distribution of stress wave transmission times (SWTTs) (in µs/ft) along the length and the mapping of physical conditions of the rider keelson and main keelson. The physical conditions of each test location were rated into four categories by comparing the measured SWTT with the reference SWTT and color-coded as follows:

🟧 **Solid: <300 µs/ft**
🟦 **Moderate decay: 300–600 µs/ft**
🟥 **Decay: 600–900 µs/ft**
🟫 **Severe decay: >900 µs/ft**

The deterioration of the keelsons is concentrated between frames 25 and 42, and most severe decay occurred on the main keelson timber between frames 30 and 39. This is also confirmed by micro-drilling resistance tests. Rainwater likely entered this area through the hatch over the years due to failed weather protection and water remained trapped. Water damage in the untested portion of the main keelson between frames 30 and 39 and even beyond could also be significant. Deterioration could be further extended and advanced with the current outdated weather protection.

No significant deterioration was found between frames 7 and 25 according to stress wave scanning results. The tween deck, which extends from frame 11 to the forward end of the hatch at frame 26, has apparently protected the keelsons from direct exposure to rainwater dripping from above (through main decking). The micro-drilling resistance test revealed isolated internal rot (5.5–9.5 in.) at the location of frame 12. A similar condition at frame 11 was reported in a 1986 survey report (Tri-Coastal Marine, Inc. 1986).

Assistant Keelsons

Assistant keelsons are deteriorated variously in the hold area. Micro-drilling resistance testing on assistant keelsons at frames 8, 32, and 48 revealed both surface decay and internal decay as shown in Table 1. An area of severe deterioration is seen between frames below the hatch.

We also observed that many surface areas of the assistant keelsons are saturated with rainwater, presumably dripping from the main deck, tween deck, or the main hatch. Moisture readings collected at many locations are well above the fiber saturation point (30%), indicating the potential of further deterioration (moisture content data are shown in Appendix C).

Keel

Stress wave scanning and mapping of the keel was done between frames 5 and 79. The scanning pattern is shown

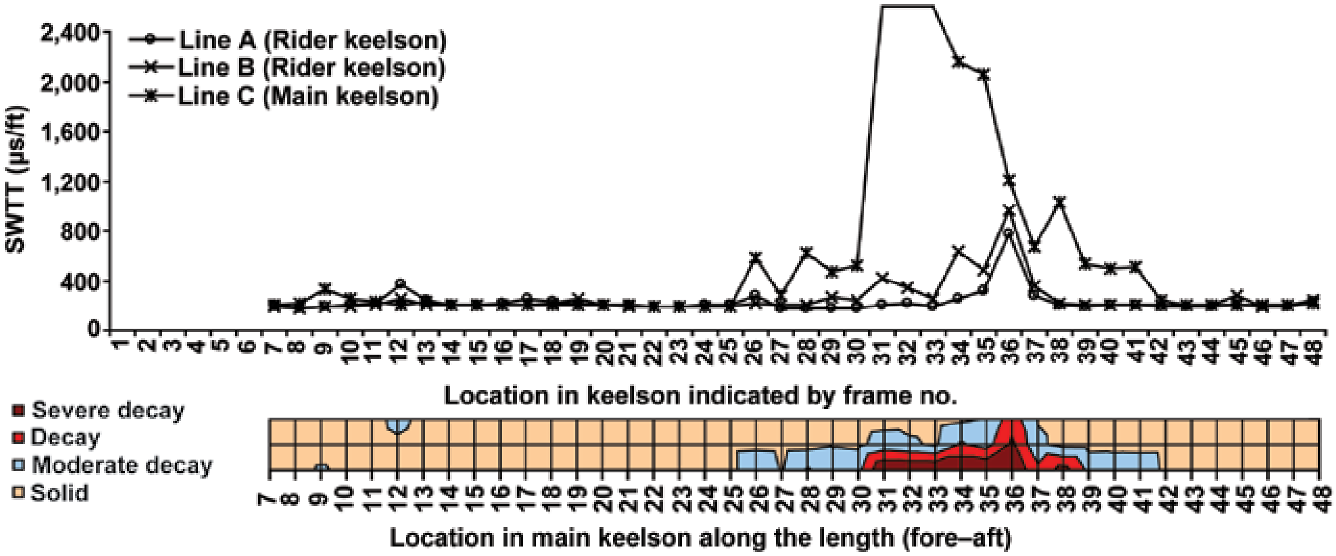

Figure 7. Distribution of stress wave transmission time (SWTT) and mapping of physical conditions of the keelsons.

Table 1. Deterioration in assistant keelsons revealed by micro-drilling resistance tests

	Starboard		Port	
Frame number	1st assistant keelson	3rd assistant keelson	1st assistant keelson	3rd assistant keelson
8	9.5–11 in. decay	N/A	N/A	N/A
32	0–2.5 in. engraver	9.5–10.5 in. decay	0–3 in. engraver 7–8.5 in. decay	0–1.5 in. decay
48	All solid	0–1.5 in. decay	0–5.5 in. decay	1–1.5 in. decay 7–8.5 in. decay

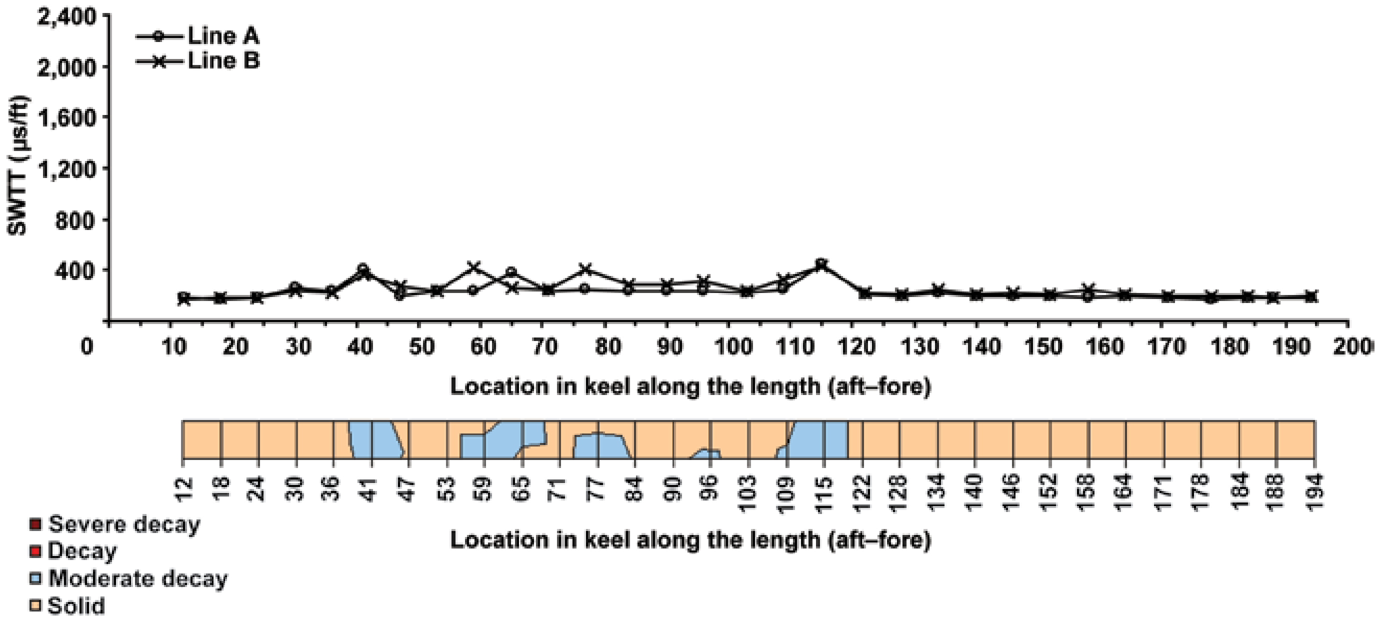

Figure 8. Distribution of stress wave transmission time (SWTT) and mapping of physical conditions of the keel.

in Figure 3b. For the convenience of quickly establishing a scan pattern, we set frame 79 (where the iron tie plate ends) as the starting point and scanning was proceeded along two lines (A and B) from aft to fore. Stress wave transmission time data were collected between the keel blocks and at 6-ft intervals. Figure 8 shows the distribution of stress wave transmission time and the mapping of physical conditions of the keel.

Moderate deterioration was found at several areas of the keel, as indicated in the mapping. Although no severe decay is present in the keel, the hogging in the mid-section of the ship has caused significant mechanical damage (shear failure) to the keel as evidenced by cracks or splits along the grain. This is confirmed by a previous report that the keel was broken when the ship was placed on Barge 214 (Tri-Coastal Marine, Inc. 1986).

Main Deck Stringers

The main deck stringers have lost most integrity due to severe deterioration. Visual signs of rot, splits, and checks are present in most portions of these members. To quantify the levels of deterioration, stress wave scanning was carried out on two side stringers with a less extensive interval (5 ft) and along the centerline of the member.

Figure 9 shows the distribution of stress wave transmission time along the length and the mapping of physical conditions of the main deck stringers.

Main Framing Timbers

The main framing timbers of the WAPAMA were evaluated through micro-drilling tests at three main cross-sections of the main hull assembly: (1) section at frame 8; (2) section at frame 32; and (3) section at frame 48 (Fig. 1). Frame 8 is located in the fore section of the cargo hold area near the vessel’s bow. Frame 32 is located mid-ship underneath the main cargo hatch. Frame 48 is located in the aft portion of the cargo hold area approximately 3 ft forward of the engine room.

Typical results from micro-drilling resistance tests showing sound wood, moderate deterioration, and severe deterioration are shown in Figure 10. Comprehensive results of all micro-drilling resistance tests are reported by NRRI (2006).

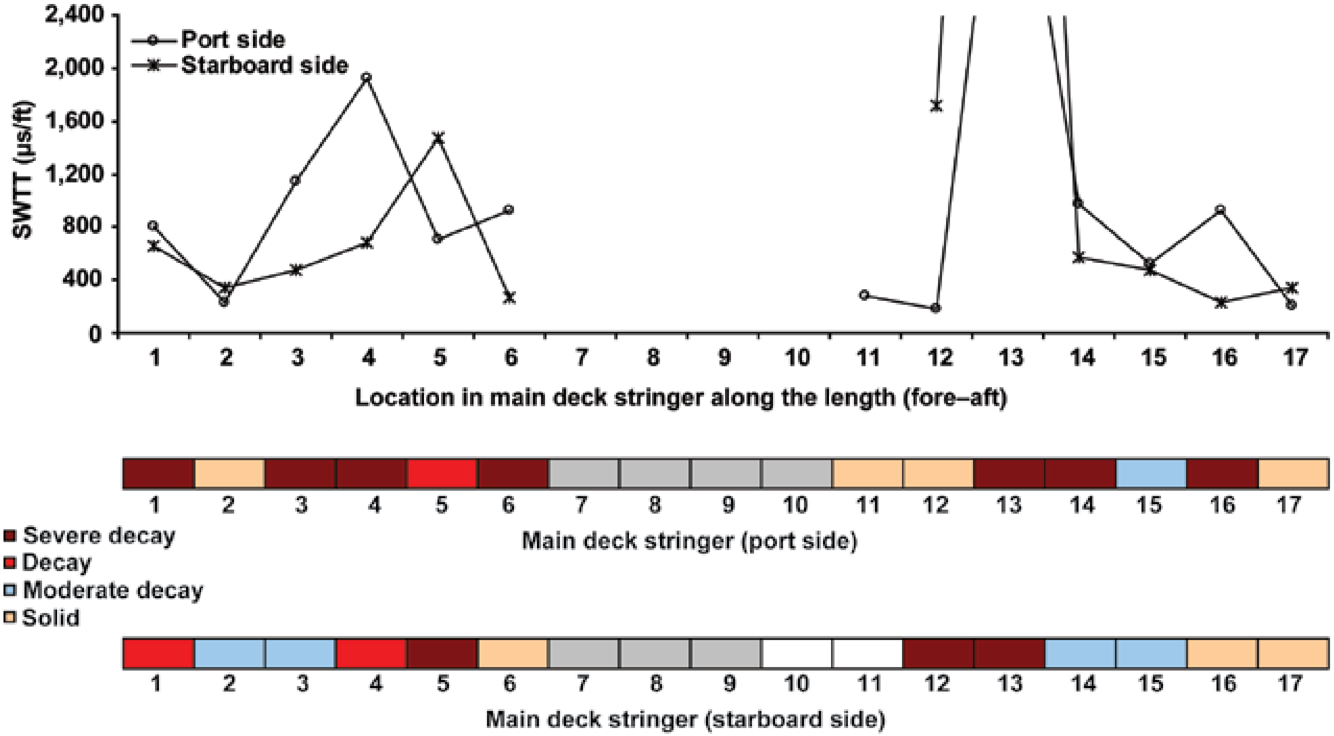

Figure 9. Stress wave transmission time (SWTT) and physical conditions of the main deck stringers.

Cross-Section at Hull Frame 8

A total of seven micro-drilling resistance measurements were collected from the hull assembly at frame 8 (Fig. 4). Safety concerns limited our access to the smaller area underneath the tween deck, therefore no data were collected from tween deck beams. From the interior of the vessel, five micro-drilling locations penetrated downward through ceiling planks and a portion of the hull frame. One additional micro-drilling location penetrated into the first assistant keelson (starboard). From the exterior of the vessel, one micro-drilling location on the starboard side penetrated upward through strake planks and a portion of the hull frame. The thickness of the interior ceiling and/or exterior strake planking varied and resulted in different penetration levels into the main frame members.

A schematic summary of micro-drilling resistance data collected at hull frame 8 is provided in Figure 11. Severe decay was detected at two of seven (29%) drilling locations at this section. Most of the ceiling planks and the first assistance keelson (starboard) are in good condition, with decay present only in the ceiling plank at drill location 2. Moderate decay was detected in the inside upper portions of the hull frame drill locations, with severe decay present at drill location 2. There were visual indicators of water seepage through overhead tween and main decks, which probably caused this deterioration since the WAPAMA was lifted onto Barge 214.

Cross-Section at Hull Frame 32

A total of 40 micro-drilling resistance measurements were collected from the hull assembly at frame 32 (Fig. 5): 18 from the interior portion of the hull assembly penetrated into clamps, ceiling planks, and assistant keelson members; 14 from topside of the main deck penetrated into bulwarks, waterways, decking, stringers, and assistance stringers; and 8 from the outer hull portions that were accessible from the barge deck.

A schematic summary of micro-drilling resistance data collected at hull frame 32 is provided in Figure 12. Severe decay was detected at 15 (38%) of the drilling locations, with most of these areas located in the members at the main deck level (stringers and main deck beams) or near the main deck level (clamps, hull frame). Deterioration of the lower hull members and keelsons was mostly moderate. Deterioration ranging from decay to severe decay was detected at nearly all drilling locations drilled downward from topside main deck. The outer waterways 19 and 30 and portside main deck planks (21 and 22) showed signs of moderate decay. Deterioration ranging from decay to severe decay was detected in clamps 1, 2, and 17, ceiling planks 5, 12, and 14, the 3rd assistant keelson portside (11), and the inside upper portion of the hull frame 1, 3, 5, 14, and 17. Drillings upward into the outer hull detected mostly sound wood with only moderate decay present in the outer lower hull frame B.

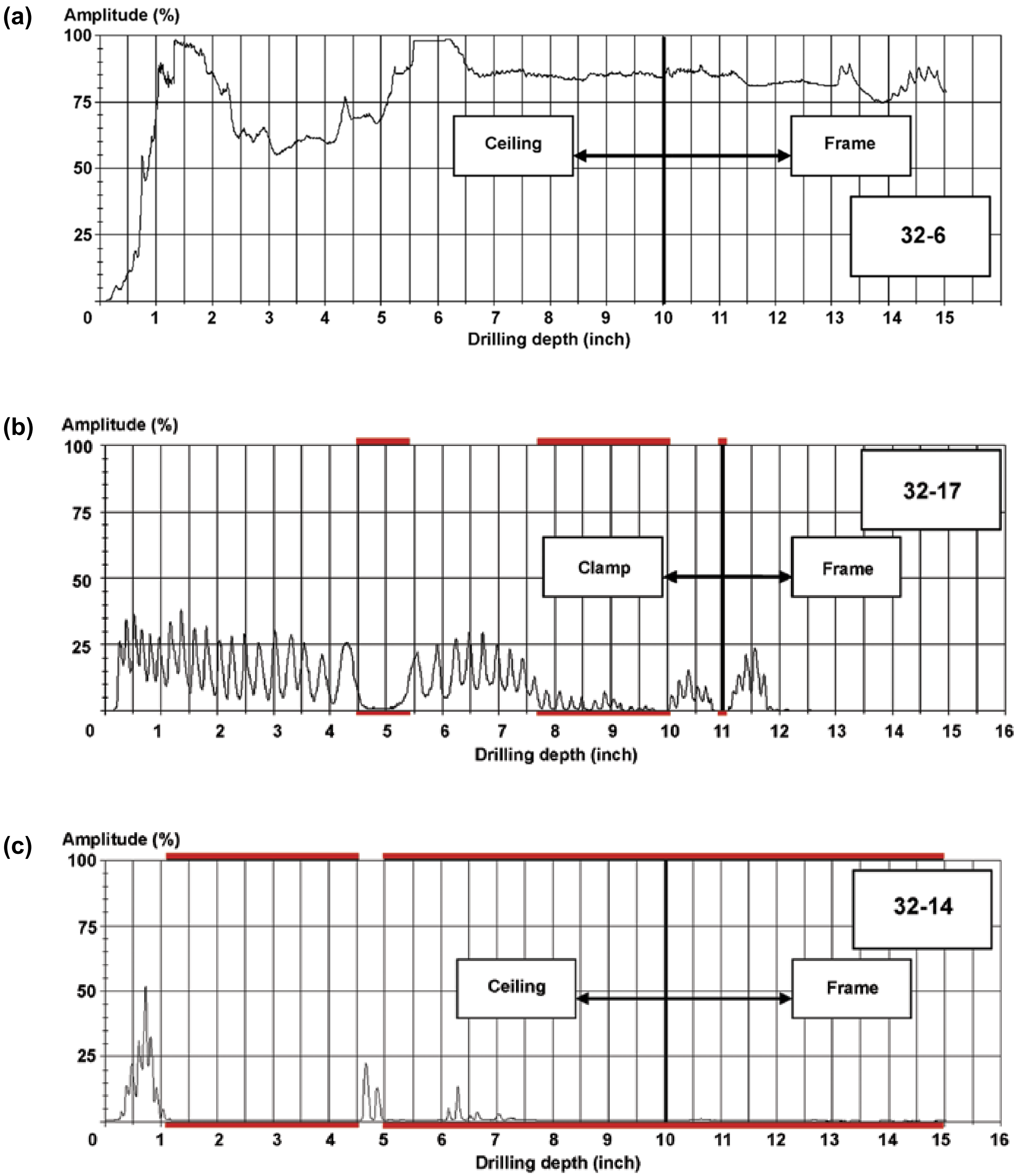

Figure 10. Typical results from micro-drilling resistance tests: (a) sound wood; (b) moderate deterioration; (c) severe deterioration.

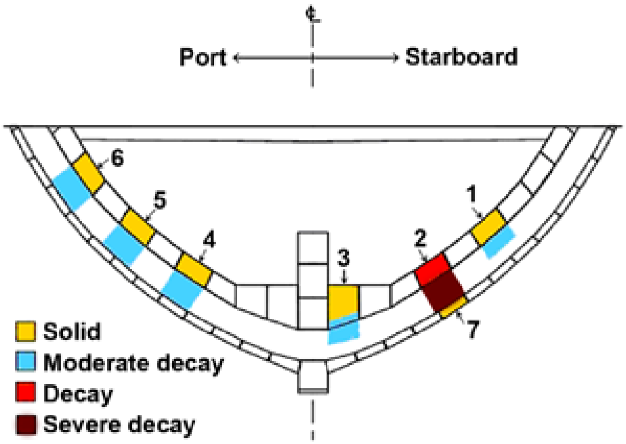

Figure 11. Mapping of physical conditions of the cross section at frame 8 (micro-drilling resistance interpretation).

Cross-Section at Hull Frame 48

A total of 40 micro-drilling resistance measurements were collected from the hull assembly at frame 48 (Fig. 6): 18 from the interior portion of the hull assembly penetrated into clamps, ceiling planks, and assistant keelson members; 14 from topside of the main deck penetrated into bulwarks, waterways, decking, stringers, and assistance stringers; and 8 from the outer hull portions that were accessible from the barge deck.

A schematic summary of micro-drilling resistance data collected at hull frame 48 is provided in Figure 13. Severe decay was detected at 12 (30%) of the drilling locations, with most of these areas located in the members at the main deck level (waterways, stringers, main deck planks, and main deck beams) or near the main deck level (clamps). Deterioration of the lower hull members and keelsons was mostly moderate. Deterioration ranging from decay to severe decay was detected at nearly all drilling locations drilled downward from topside main deck, except main deck plank 22. Deterioration ranging from decay to severe decay was also detected in clamps 2, 16, 17, and 18, the 1st assistant keelson portside (10), ceiling planks 12 and 13, and the inside upper portion of the hull frame 18. Drillings upward into the outer hull detected mostly sound wood, with deterioration noted only in outer hull plank A and in outer hull plank/hull frame H.

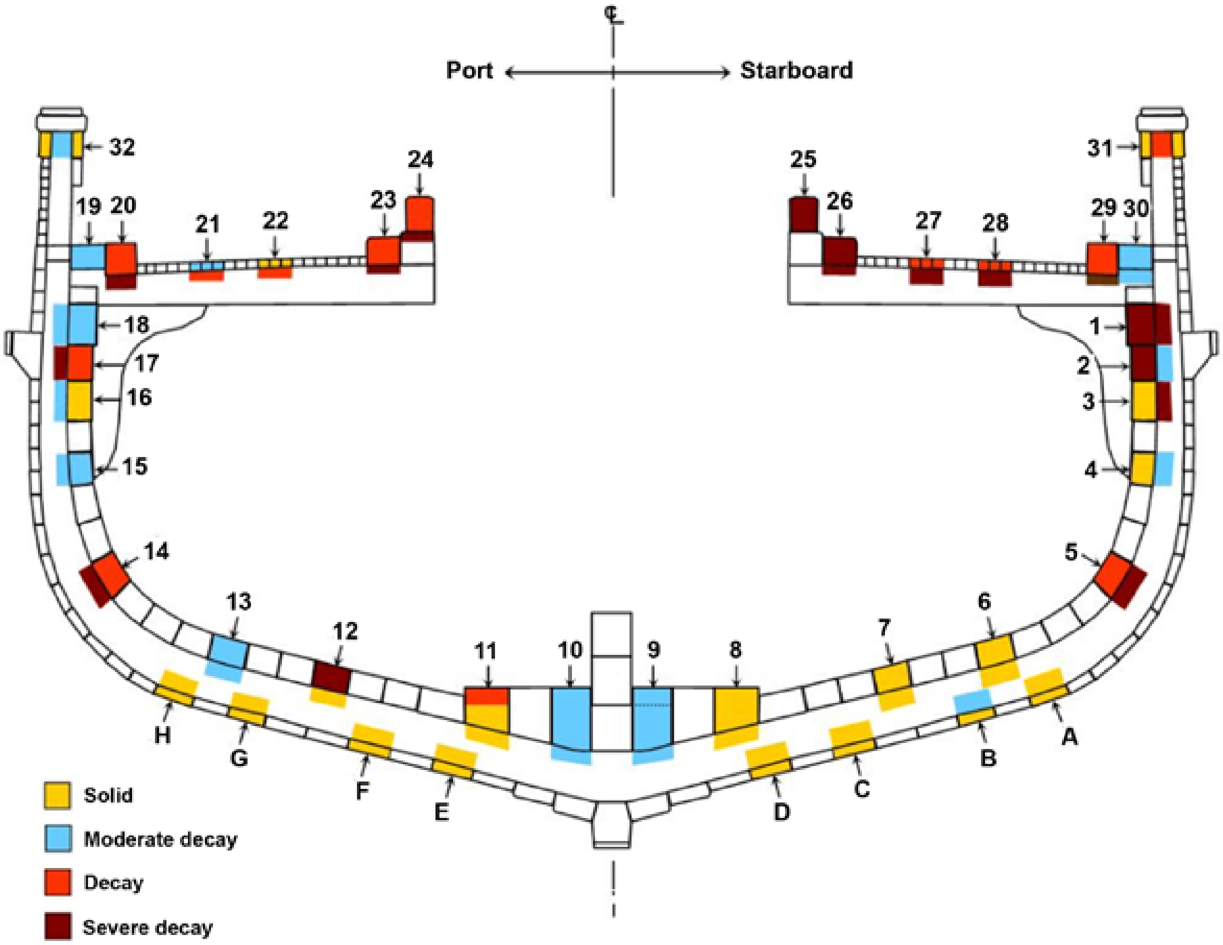

Figure 12. Mapping of physical conditions of the cross-section at frame 32 (micro-drilling resistance interpretation).

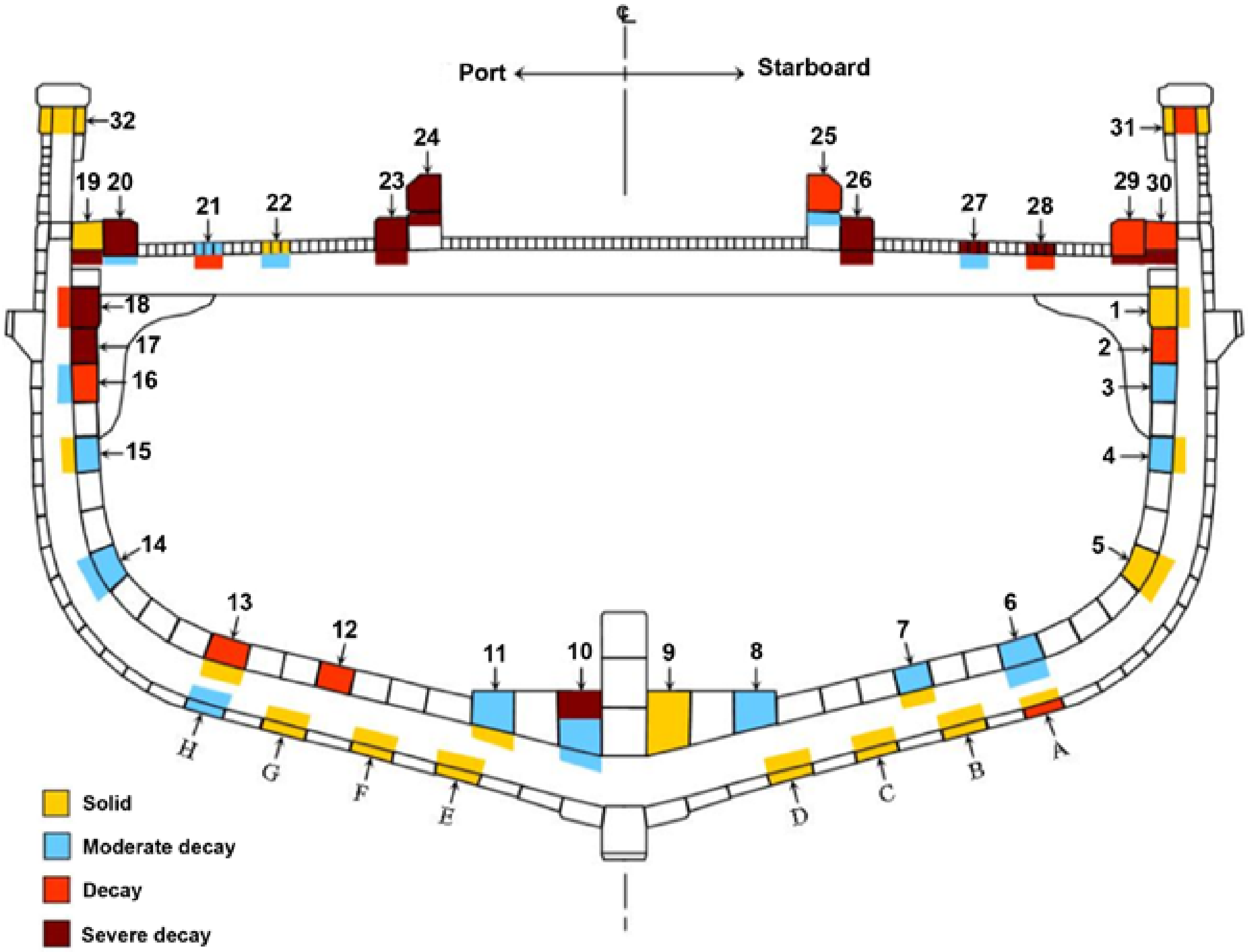

Figure 13. Mapping of physical conditions of the cross-section at frame 48 (micro-drilling resistance interpretation).

Main Deck Beams

Stress wave transmission data were collected from the main deck beams at two areas on the ship's portside (Fig. 14). Five test locations were in the main deck beams above the tween deck, including some at the hanging knees (Fig. 14a). An additional five test locations were in the rear cargo hold between the main hatch and the cabin deck (Fig. 14b). A summary of the condition of the main deck beams is provided in Table 2 and Figure 15.

Beams above Tween Deck

Stress wave transmission data confirmed that the main deck beams above the tween deck are in an advanced state of deterioration. Decay and severe decay were detected at all beams, as indicated by the stress wave transmission times in Table 2. Beams located at or near hull frames 13, 15, 20, 22, 24, and 26 have almost lost their entire strength and are considered having zero load capacity. In addition, severe deterioration was found in the hanging knees at frames 15 and 26, which raises serious concerns on the rest of the hanging knees that have not been tested.

Beams at Rear Cargo Hold

The condition of the main deck beams at rear cargo hold varied. Decay to severe decay is present at the beam ends over the stanchion for most beams. The exception is the deck beam located near hull frame 44, which is sound. At the beam ends near the outer hull frame, only the beam at hull frame 40 shows decay, the beams near frames 38 and 46 shows moderate decay, and the beams near 42, 44, and 48 are generally sound. The condition of the main deck beams away from their supports is mostly sound, with moderate deterioration detected at some beams. The main deck beam in the best condition is at hull frame 44. Severe deterioration was present only at the end support (over the stanchion) at hull frame 42.

Vertical Supporting Columns

The physical conditions of 6 pillars and 20 hold stanchions were evaluated with stress wave transmission technique. The pillars were located in the aft part of the ship, with their length spanning the hold to the boat deck. The hold stanchions are located in the hold of the ship and support the main deck beams. Member testing took place in two

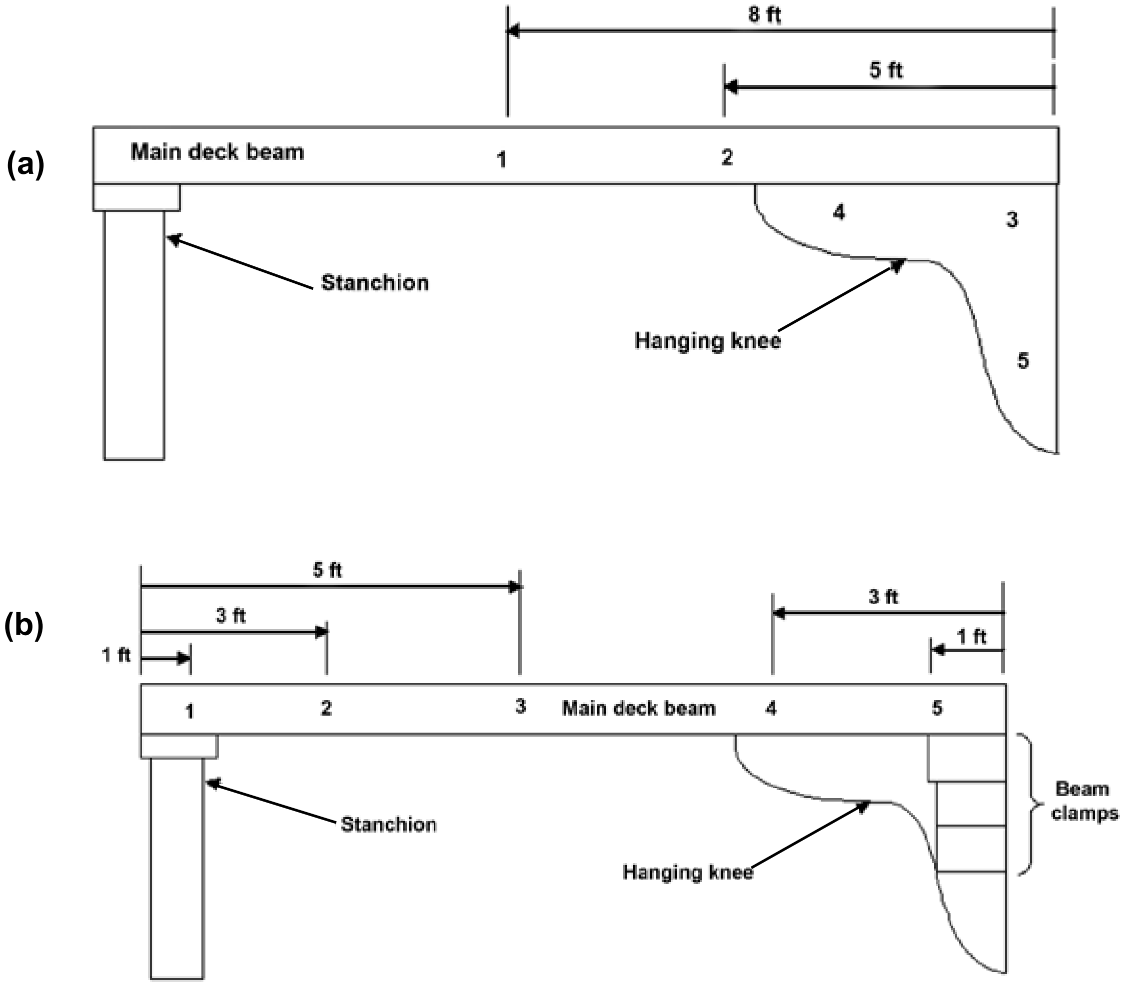

Figure 14. Stress wave testing locations for portside main deck beams: (a) main deck beams and hanging knees above tween deck; (b) main deck beams at rear cargo hold.

directions—the fore-to-aft direction (in which the test faces were to the forward and aft of the ship) and the port-to-starboard direction (in which the test faces were to the port and starboard directions of the ship).

Pillars

The pillars were tested at three levels of the ship: engine/boiler room (lower level), main deck (middle level), and cabin deck (upper level). The lower level of the ship allowed access to fore-to-aft and port-to-starboard faces on all six pillars (A–F, Fig. 16), whereas the main deck allowed access only to four pillars, those in the forward part of the cabin deck house (A–D), and in the fore-to-aft direction. The pillars accessible on the upper level (cabin deck house) were the two in the foremost part of the engine room (A and B), and they were accessible only in the port-to-starboard direction. Table 3 summarizes the physical conditions of the pillars evaluated by stress wave tests (the stress wave transmission data of the pillars are shown in Appendix B7). Deterioration is present in most pillars, but varies at different levels (lower, middle, and upper). Pillars A and B show moderate deterioration in the lower level, decay in the middle level, and are sound in the upper level. Pillars C and D have areas of moderate deterioration and decay in the lower and/or middle level, whereas pillars E and F are found in sound condition in the lower level. Because pillars E and F could be accessed and tested only at one level of the ship, results are not conclusive for the entire members.

Hold Stanchions

The hold stanchions were first visually assessed for deterioration, and then a subset of the members was spot-checked with stress wave transmission testing. The hold stanchions tested were numbers 1–3, 5, 7–10, 13–15, 17, and 20 (Fig. 16). Hold stanchions 1, 2, and 3 were found to have moderate decay, with stress wave transmission times ranging from 326 to 584 µs/ft. The remaining hold stanchions were found to be solid, with stress wave transmission times ranging from 179 to 200 µs/ft.

Table 2. Stress wave transmission time (SWTT) and physical conditions of the portside main deck beams and hanging knees

Portside beam location	Frame number	Relative deterioration level and SWTT (µs/ft)				
		Main deck beams		Hanging knees		
		1	2	3	4	5
Above tween deck	26	Severe 1,051	Moderate 397	Severe 4,948	Severe 2,966	Severe 3,050
	24	Decay 700	Severe 828	—	—	—
	22	Severe 3,087	Severe 4,374	—	—	—
	20.5	Severe 1,551	Severe 3,126	—	—	—
	18.5	Decay 759	Moderate 568	—	—	—
	16.5	Moderate 555	Decay 742	Decay 621	Severe 933	Severe 999
	14.5	Severe 4,783	Severe 4,997	—	—	—
	12.5	Severe 4,966	Severe 5,379	—	—	—
		Main deck beams				
		1	2	3	4	5
Rear cargo hold	38.5	Decay 736	Sound 221	Sound 225	Moderate 575	Moderate 378
	40	Decay 678	Moderate 442	Sound 206	Moderate 474	Decay 698
	42	Severe 969	Moderate 329	Sound 187	Sound 230	Sound 190
	44	Sound 177	Sound 207	Moderate 427	Sound 282	Sound 209
	45.5	Decay 628	Sound 254	Sound 222	Sound 249	Moderate 486
	47.5	Moderate 429	Moderate 529	Sound 204	Sound 296	Sound 292

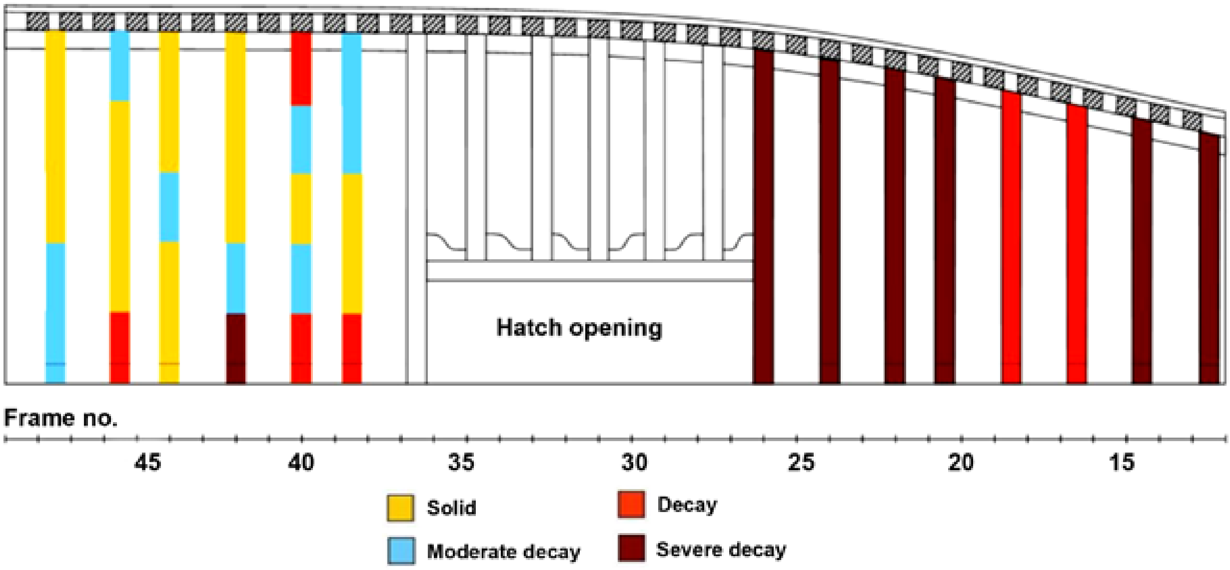

Figure 15. Mapping of physical conditions of portside main deck beams (plan view).

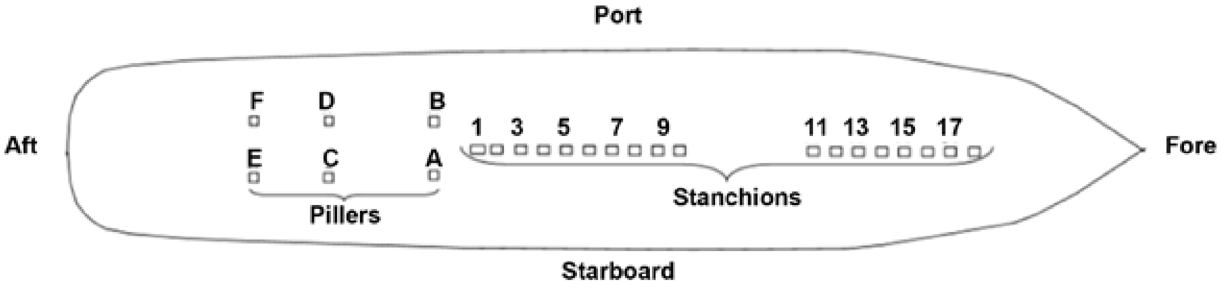

Figure 16. Location of pillars and stanchions on the ship (plan view).

Table 3. Physical conditions of the pillars evaluated by stress wave tests[a]

	Deck level		
Pillar	Lower	Middle	Upper
A	Moderate	Decay	Solid
B	Moderate	Decay	Solid
C	Decay	Moderate	NA
D	Moderate	Solid	NA
E	Solid	NA	NA
F	Solid	NA	NA

[a] NA, not accessible.

Pointers

The pointers tested were the second pointers in the front of the ship accessible by the tween deck in the hold. There is one pointer on each side of the boat, and they were labeled as the port and starboard pointers. The pointers were spot-checked with stress waves at 4-ft intervals beginning at the foremost part of the member. Results show that the pointers are generally in a sound condition. The aftmost 4 ft on the portside pointer and the aftmost 8 ft on the starboard pointer each had a large crack that resulted in moderate levels of deterioration, but the remaining length of each member was solid. Stress wave transmission times ranged from 190 to 287 µs/ft in solid areas and from 460 to 518 µs/ft in moderately decayed areas.

Summary of Findings

A general condition assessment of the historic steam schooner, WAPAMA, was conducted over a 4-day period in January 2006. Our investigation focused on the key structural components that provide the structural integrity of the vessel. Structural components tested that provide for longitudinal integrity are the keelsons (rider keelson, main keelson, assistant keelsons), main deck stringers, waterways, bulwarks, and keel. Structural components tested that provide for transverse integrity are the hull assembly (framing timbers, ceiling, clamps, strakes) at three cross-sections and the main deck beams. Due to limited inspection time, the investigation was not intensively focused on individual members, but instead was conducted with relatively large scan intervals or through spot-checking of suspected areas. Stress-wave timing and micro-drilling resistance were the primary methods used in this investigation, coupled with visual inspection and moisture content determination.

Condition of Structural Components

Keelsons

The rider keelson and main keelson (top tier) were evaluated between frames 7 and 48 with stress wave scanning and micro-drilling resistance testing. Advanced deterioration of the keelsons was concentrated under the main hatch area. The rider keelson was deteriorated between frames 30 and 39, and the main keelson (top tier) was deteriorated between frames 25 and 42. No significant deterioration was detected in the keelsons under the tween deck between frames 7 and 25. Assistant keelsons were evaluated by micro-drilling resistance (topside downward) at frames 8, 32, and 48. Resistance plots indicated only isolated pockets of moderate decay.

Main Deck Stringers

The main deck stringers were spot-checked with stress-wave timing and micro-drilling resistance testing. Severe deterioration was confirmed in both side stringers and assistant stringers. Overall, the main deck stringers have lost nearly all structural integrity.

Waterways and Bulwarks

Waterways and bulwarks were evaluated at several locations with micro-drilling resistance testing at the main deck. Most severe deterioration was present in the waterways, whereas many of the bulwarks had moderate to severe decay.

Keel

The keel was evaluated at 6-ft intervals (between the keel blocks) with stress-wave timing and spot-checked by micro-drilling resistance. Moderate deterioration was present at several locations in the aft half of the keel. Visual signs of large splits and cracks may indicate that the keel was broken while the vessel was lifted onto Barge 214.

Hull Assembly

The hull assembly was evaluated at frames 8, 32, and 48 using micro-drilling resistance techniques. The condition of the hull assembly at frame 8 is generally good, with moderate decay present in the ceiling and framing timbers. Severe deterioration was confirmed at one location near the assistant keelson with both inboard and outboard drilling data. The condition of the lower hull assemblies at frames 32 and 48 is good, with minor pockets of decay present at a few locations. All clamps and upper framing timbers at frames 32 and 48 have moderate to severe decay present.

Main Deck Beams

The main deck beams at the portside of the vessel were spot-checked with stress wave timing. Severe deterioration was found in nearly all main deck beams above the tween deck. Test results indicate that these beams have lost entire structural integrity and have potential to collapse in the near future, which poses a significant safety hazard. The main deck beams at the rear cargo hold area are mostly sound, with moderate to severe decay found at the end support areas.

Condition of the Vessel by Areas

Area under Cabin Decks

Findings for the aft portion of the vessel beneath the cabin decks were largely based on visual assessment. These areas appeared to be generally in good condition as they were similarly reported in the 1986 condition assessment (Tri-Coastal Marine, Inc. 1986).

Main Cargo Hold to Tween Deck

Findings for the midship portion of the vessel extending from the cabin deck to forward hatch side were largely based upon NDE techniques. Significant areas of decay were noted in the following longitudinal structural components: the portion of the rider and main keelson under the main hatch, main deck stringers, and waterways. Significant areas of decay were noted in the following transverse structural components: clamps and framing timbers near waterways, main deck beams, and main deck planking. The lower hull assembly at frames 32 and 48 showed isolated pockets of significant decay.

Tween Deck Forward

Findings for the forward portion of the vessel from the main hatch forward were largely based upon NDE techniques. Significant areas of decay were noted in main deck stringers, waterways, bulwarks, and main deck beams. The main deck beams located over the tween deck are in bad condition with severe internal decay. The lower hull assembly at frame 8 showed an isolated pocket of severe decay.

Recommendations

The following recommendations are provided based upon our findings from this on-site investigation:

Repair or replacement of the temporary roof shelter over the main deck is recommended. The current weather protection over the main deck is clearly ineffective in preventing intrusion of rainwater, as evidenced by water seepage from the underside vents in the outer hull. Moisture is saturating several key structural components on the main deck and in the cargo hold. An effective roof will prevent further decay until restoration work is initiated.

Should the decision be made to disassemble the WAPAMA, more intensive NDE scanning and analysis of key structural components is recommended during the restoration process. This will provide more accurate assessment of the extent of internal deterioration and can help in making decisions to retain key components or to salvage portions of key components for non-structural members elsewhere in the restored vessel.

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Appendix A—Photographic Documentation

Starboard side view

Port side view

Aft view of starboard outer hull

Side view of starboard outer hull

Portside view of propeller/rudder assembly

Hull planks removed to vent cargo hold (note rainwater seepage)

Fore view of keel and hull bottomside

Aft view of main deck area showing main cargo hatch and overhead roof structure

Starboard view of deteriorated waterway and main decking

Aft view of main cargo hold showing ceilings, clamps, hanging knees, main deck beams

Stress wave timing measurements at main deck beam

Stress wave timing measurements at hanging knee

Resistance micro-drilling a clamp member

Appendix B—Stress Wave Data Summary

B1—Keelsons

Dimension: 20 × 17.5 in. Test Interval: 2 ft 6 in. Date: January 10, 2006

	Rider keelson										Main keelson					
	Line A					Line B					Line C					
Frame no.	Stress wave time (µs) 1	2	3	Avg.	Velocity (µs/ft)	Stress wave time (µs) 1	2	3	Avg.	Velocity (µs/ft)	Stress wave time (µs) 1	2	3	Avg.	Velocity (µs/ft)	Note
1–6																Not accessible
7	334			334	203	309			309	188	345			345	210	
8	295			295	179	288			288	175	354			354	215	
9	321			321	195	313	321	315	316	192	439	729	445	538	327	
10	330	332	348	337	205	320	316	318	318	193	411	411	415	412	251	
11	368	363	358	363	221	324	326	324	325	197	372	375	378	375	228	
12	600	588	603	597	363	423	428	427	426	259	346	338	340	341	207	
13	396	404	403	401	244	328	328	327	328	199	357	375	380	371	225	
14	316	332	330	326	198	330	334	331	332	202	342	322	351	338	206	
15	343	357	333	344	209	332	333	326	330	201	333	333	334	333	203	
16	352	340	351	348	211	333	320	324	326	198	331	342	342	338	206	
17	441	423	421	428	260	334	332	328	331	201	336	332	339	336	204	
18	385	386	385	385	234	344	344	351	346	210	325	325	325	325	197	
19	356	368	367	364	221	414	417	410	414	251	339	334	348	340	207	
20	331	321	322	325	197	343	344	342	343	208	344	348	337	343	208	
21	336	326	322	328	199	320	316	314	317	192	327	327	327	327	199	
22	325	318	319	321	195	321	320	322	321	195	321	325	322	323	196	
23	315	316	315	315	192	315	315	314	315	191	306	309	306	307	187	
24	337	345	343	342	208	324	326	318	323	196	327	313	309	316	192	
25	333	336	348	339	206	318	322	324	321	195	318	309	316	314	191	
26	480	463	465	469	285	367	343	361	357	217	942	953	962	952	579	
27	298	291	295	295	179	322	327	324	324	197	446	453	457	452	275	
28	306	302	291	300	182	338	336	342	339	206	982	948	1172	1034	628	
29	288	300	286	291	177	442	446	459	449	273	766	769	756	764	464	
30	291	296	301	296	180	387	403	405	398	242	453	489	1620	854	519	
31	332	342	333	336	204	679	698	684	687	417						Decay
32	356	351	351	353	214	567	566	572	568	345						Decay
33	314	321	314	316	192	453	412	411	425	258						Engraver
34	417	420	415	417	254	1029	1048	1045	1041	632	3757	3747	3144	3549	2157	Engraver
35	518	517	518	518	315	784	776	795	785	477	3393	3380	3398	3390	2060	Engraver, decay
36	1261	1265	1286	1271	772	1590	1580	1596	1589	965	2239	2343	1388	1990	1209	Engraver
37	476	462	462	467	284	589	588	590	589	358	1111	1118	1086	1105	671	Engraver
38	324	328	322	325	197	342	348	349	346	210	1681	1688	1696	1688	1026	
39	314	318	318	317	192	328	330	327	328	199	848	828	930	869	528	Surface decay
40	327	326	327	327	198	346	344	343	344	209	806	825	807	813	494	C: decay
41	330	330	327	329	200	332	331	331	331	201	838	820	825	828	503	
42	324	319	321	321	195	338	337	339	338	205	399	400	390	396	241	C: surface rot
43	310	313	312	312	189	325	325	324	325	197	340	343	345	343	208	
44	318	314	312	315	191	327	327	330	328	199	339	338	332	336	204	
45	325	324	326	325	197	727	330	327	461	280	327	324	327	326	198	
46	309	307	303	306	186	301	313	320	311	189	336	337	338	337	205	
47	318	320	322	320	194	343	344	343	343	209	325	326	328	326	198	
48	387	385	382	385	234	398	399	393	397	241	350	346	348	348	211	

B2—Keel

Dimension: 16 × 20 in. Test Interval: 6 ft Date: January 12–13, 2006

Location[a] (ft)	Line A					Line B					Note
	Stress wave time (μs)				Velocity (μs/ft)	Stress wave time (μs)				Velocity (μs/ft)	
	1	2	3	Avg.		1	2	3	Avg.		
12	294	301	296	297	178	283	279	282	281.3	169	
18	280	274	266	273	164	301	295	292	296.0	178	
24	310	312	308	310	186	303	301	303	302.3	181	
30	428	428	424	427	256	400	384	379	387.7	233	
36	390	390	385	388	233	376	361	351	362.7	218	
41	686	670	668	675	405	618	606	615	613.0	368	
47	333	334	330	332	199	466	466	465	465.7	279	
53	381	382	385	383	230	387	387	388	387.3	232	
59	397	398	396	397	238	715	707	674	698.7	419	
65	658	636	627	640	384	435	433	433	433.7	260	
71	406	397	387	397	238	418	410	412	413.3	248	
77	429	423	417	423	254	667	661	679	669.0	401	
84	390	391	393	391	235	483	471	468	474.0	284	
90	399	397	397	398	239	482	476	474	477.3	286	
96	385	382	387	385	231	531	529	534	531.3	319	
103	373	372	369	371	223	396	388	390	391.3	235	
109	420	423	423	422	253	553	538	536	542.3	325	
115	746	735	740	740	444	718	715	697	710.0	426	Big crack
122	337	342	336	338	203	362	362	356	360.0	216	
128	324	319	316	320	192	352	348	345	348.3	209	
134	380	379	381	380	228	417	426	424	422.3	253	
140	325	331	326	327	196	355	355	356	355.3	213	
146	320	322	322	321	193	378	373	374	375.0	225	
152	327	334	336	332	199	345	345	342	344.0	206	
158	312	311	310	311	187	408	414	414	412.0	247	
164	320	322	318	320	192	352	350	349	350.3	210	
171	307	309	306	307	184	350	327	328	335.0	201	
178	276	277	277	277	166	319	321	320	320.0	192	
184	300	304	303	302	181	334	335	337	335.3	201	
188	312	310	312	311	187	308	308	303	306.3	184	
194	310	308	304	307	184	316	318	320	318.0	191	

[a] Numbers represent distance from aft to fore of the ship.

B3—Main Deck Beams above Tween Deck (Portside)

Dimensions: 14.5 × 14.5 in. Test Interval: Spot check Date: January 11, 2006

Frame no.	Location 1					Location 2					Location 3				
	Stress wave time (µs)				Velocity (µs/ft)	Stress wave time (µs)				Velocity (µs/ft)	Stress wave time (µs)				Velocity (µs/ft)
	1	2	3	Avg.		1	2	3	Avg.		1	2	3	Avg.	
12.5	242	244	244	243	201	228	224	222	225	186					
14.5	256	256	259	257	209	247	247	244	246	200					
16.5	2246	2206	2196	2216	1803	1654	1632	1684	1657	1348	2035	1419	1418	1624	1659
18.5	1476	1562	1870	1636	1331	2013	2253	2245	2170	1766					
20.5	790	792	796	793	645	403	393	384	393	320					
22	396	399	380	392	324	283	274	272	276	229					
24	1735	1722	1722	1726	1429	1495	1410	1476	1460	1209					
26	1316	1303	1306	1308	952	3460			3460	2516	194	204	196	198	202

Frame no.	Location 4					Location 5				
	Stress wave time (µs)				Velocity (µs/ft)	Stress wave time (µs)				Velocity (µs/ft)
	1	2	3	Avg.		1	2	3	Avg.	
12.5										
14.5										
16.5	1063	1046	1041	1050	1072	1242	1238	980	1153	1178
18.5										
20.5										
22										
24										
26	310	392	302	335	342	324	307	321	317	324

B4—Main Deck Beams at Rear Cargo Hold (Portside)

Dimensions: 14.5 × 14.25 in. Test Interval: Spot check Date: January 11, 2006

	Location 1					Location 2					Location 3				
	Stress wave time (µs)					Stress wave time (µs)					Stress wave time (µs)				
Frame no.	1	2	3	Avg.	Velocity (µs/ft)	1	2	3	Avg.	Velocity (µs/ft)	1	2	3	Avg.	Velocity (µs/ft)
38.5	849	1004	860	904	736	270	266	278	271	221	277	273	279	276	225
40	754	928	777	820	678	532	531	541	535	442	247	249	249	248	206
42	1195	1191	1186	1191	969	408	403	402	404	329	225	229	236	230	187
44	211	217	214	214	177	247	253	249	250	207	512	518	518	516	427
45.5	762	757	759	759	628	312	304	306	307	254	268	270	268	269	222
47.5	520	517	519	519	429	634	640	645	640	529	244	250	244	246	204

	Location 4					Location 5				
	Stress wave time (µs)					Stress wave time (µs)				
Frame no.	1	2	3	Avg.	Velocity (µs/ft)	1	2	3	Avg.	Velocity (µs/ft)
38.5	715	692	714	707	575	462	471	460	464	378
40	561	567	592	573	474	876	831	824	844	698
42	283	284	280	282	230	232	235	232	233	190
44	342	334	346	341	282	253	254	252	253	209
45.5	298	301	302	300	249	586	588	589	588	486
47.5	358	358	356	357	296	350	354	355	353	292

B5—Main Deck Stringers

Dimensions: 11.5 × 13.5 in. Test Interval: 5 ft Date: January 12, 2006

Portside Side Stringer

	Stress wave time (µs)				Velocity	
Location[a]	1	2	3	Avg.	(µs/ft)	Note
1	754	759	752	755	805	
2	226	222	219	222	237	
3	1036	1148	1036	1073	1145	
4	1810	1789	1814	1804	1925	
5	659	652	666	659	703	
6	861	866	867	865	922	Repaired
7						Repaired
8						Repaired
9						Repaired
10						Repaired
11	266	260	265	264	281	
12	180	169	174	174	186	
13	4117	4069	4035	4074	4345	
14	932	916	906	918	979	
15	490	494	489	491	524	
16	867	859	886	871	929	
17	193	195	196	195	208	

[a] Numbers represent 5-ft intervals from fore to aft of the ship.

Starboard Side Stringer

	Stress wave time (µs)				Velocity	
Location[a]	1	2	3	Avg.	(µs/ft)	Note
1	615	619	609	614	655	
2	318	314	314	315	336	
3	444	439	444	442	472	
4	644	646	642	644	687	
5	1381	1377	1394	1384	1476	
6	249	246	254	250	266	
7	2574	2548	2582	2568	2739	Repaired
8	1862	1575	1550	1662	1773	Repaired
9	1953	2158	2229	2113	2254	Netting in way
10						Netting in way
11						Netting in way
12	1632	1620	1593	1615	1723	
13	8977	8972	8935	8961	9559	
14	540	544	540	541	577	
15	459	452	429	447	476	
16	222	210	207	213	227	
17	322	327	319	323	344	

[a] Numbers represent 5-ft intervals from fore to aft of the ship.

B6—Pointers

Dimensions: 14 × 13 in. Test Interval: 4 ft Date: January 12, 2006

Starboard Pointer

Location[a]	Stress wave time (µs) 1	2	3	Avg.	Velocity (µs/ft)	Note
1	226	249	235	237	210	
2	244	246	246	245	218	
3	214	218	214	215	191	
4	224	225	224	224	199	
5	225	226	224	225	200	
6	276	260	261	266	236	Big crack
7	547	544	528	540	480	Big crack
8	585	582	582	583	518	Big crack

[a] Numbers represent 4-ft intervals from fore to aft of the ship.

Portside Pointer

Location[a]	Stress wave time (µs) 1	2	3	Avg.	Velocity (µs/ft)	Note
9	226	230	226	227	202	
10	244	252	241	246	218	
11	229	223	223	225	200	
12	226	224	229	226	201	
13	243	254	246	248	220	
14	204	218	218	213	190	
15	325	321	324	323	287	
16	524	511	516	517	460	Big crack

[a] Numbers represent 4-ft intervals from fore to aft of the ship.

B7—Pillars

Dimensions: 15 × 15.5 in. Test Interval: Spot check Date: January 11, 2006

Pillar	Test location	Test direction	Floor level	Stress wave time (µs)				Velocity (µs/ft)
				1	2	3	Avg.	
A	1	Fore–aft	Lower	344	342	345	344	266
A	1	Port–starboard	Lower	462	451	440	451	349
A	2	Fore–aft	Lower	495	494	493	494	382
A	2	Port–starboard	Lower	1011	1026	1014	1017	787
A	1	Fore–aft	Middle	459	469	468	465	360
A	2	Fore–aft	Middle	822	825	823	823	638
A	1	Port–starboard	Upper	214	213	214	214	166
B	1	Fore–aft	Lower	702	703	708	704	545
B	1	Port–starboard	Lower	540	540	538	539	418
B	2	Fore–aft	Lower	668	623	627	639	495
B	2	Port–starboard	Lower	314	312	308	311	241
B	1	Fore–aft	Middle	321	321	327	323	250
B	2	Fore–aft	Middle	1034	1030	1002	1022	792
B	1	Port–starboard	Upper	253	250	247	250	193
C	1	Fore–aft	Lower	608	609	609	609	471
C	1	Port–starboard	Lower	1012	919	1011	981	759
C	2	Fore–aft	Lower	483	472	465	473	366
C	2	Port–starboard	Lower	762	721	756	746	578
C	1	Fore–aft	Middle	300	315	308	308	238
C	2	Fore–aft	Middle	688	682	682	684	530
D	1	Fore–aft	Lower	331	343	347	340	263
D	1	Port–starboard	Lower	686	614	685	662	512
D	2	Fore–aft	Lower	482	484	477	481	372
D	2	Port–starboard	Lower	402	394	402	399	309
D	1	Fore–aft	Middle	416	404	402	407	315
D	2	Fore–aft	Middle	368	357	346	357	276
E	1	Port–starboard	Lower	243	242	237	241	186
E	2	Port–starboard	Lower	258	261	255	258	200
F	1	Port–starboard	Lower	291	297	295	294	228
F	2	Port–starboard	Lower	316	301	304	307	238

B8—Hold Stanchions

Dimensions: 7.5 × 14.5 in. Test Interval: Spot check Date: January 11, 2006

No.[a]	Test line	Test direction	Floor level	Stress wave time (µs) 1	2	3	Avg.	Velocity (µs/ft)
0	A	Fore–aft	Lower	817	811	780	803	584
0	B	Fore–aft	Lower	496	510	441	482	351
1	A	Fore–aft	Lower	727	723	735	728	514
1	B	Fore–aft	Lower	668	660	663	664	468
2	A	Fore–aft	Lower	386	393	403	394	326
4	A	Fore–aft	Lower	226	226	224	225	186
6	A	Fore–aft	Lower	234	229	229	231	191
8	A	Fore–aft	Lower	235	241	232	236	195
9	A	Fore–aft	Lower	246	243	237	242	200
12	A	Fore–aft	Lower	231	225	235	230	191
14	A	Fore–aft	Lower	236	240	236	237	196
16	A	Fore–aft	Lower	240	242	242	241	200
19	A	Fore–aft	Lower	180	177	180	179	179

Appendix C—Moisture Content Data Summary

Date: January 11–13, 2006

Member	Location	Moisture content (%) at three pin penetration depths[a]		
		1 in.	2 in.	3 in.
Keelson	37-A	33	38	40
	37-B	37	40	38
	35-A	28	31	42
	35-B	32		80
	48-A	51	46	62
	48-B	50	42	45
	46-A	40	23	27
	46-B	49	35	31
	46-C	54	53	48
	43-A	41	30	28
	43-B	44	32	27
	43-C	85	62	45
	7-A	55	53	38
	10-A	34	40	30
Keel	12	27	26	33
	109	38	40	50
	194	44	53	57
Pointer	2	63	43	29
	4	47	38	24
	6	47	43	80
	10	80	68	47
	12	28	40	51
	14	23	21	26
Pillar[b]	AA-Lower	23	23	24
	BA-Lower	30	36	30
	CA-Lower	14	16	17
	DA-Lower	80	80	
	EA-Lower	15.5	17.5	16
	FA-Lower	15.5	15	15
	AA-Main	18	23	23
	BA-Main	20	20	23
Main framing timbers[c]	36-1	25	23	22
	36-2	31	25	28
	36-3	30	25	23
	32-1	29	32	31
(Hull assembly—cont.)	32-2	27	28	25
	32-3	25	27	26
	32-4	31	28	29
	32-5	80	80	80
	32-6	39	37	33
	32-7	32	33	35
	32-8	33	41	36
	32-9	22	24	22
	32-10	28	28	28
	32-11	30	29	25
	32-12	80	80	80
	32-13	31	32	33
	32-14	80	80	80
	32-15	35	35	33
	32-16	37	39	41
	32-17	29	27	26
	32-18	35	33	32
	48-1	33	29	32
	48-2	36	32	31
	48-3	31	30	28
	48-4	37	37	80
	48-5	32	30	31
	48-6	30	29	28
	48-7	41	39	33
	48-8	80	57	53
	48-9	63	80	80
	48-10	30	45	43
	48-11	80	53	53
	48-12	48		80
	48-13	39	42	45
	48-14	45	47	43
	48-15	55	48	42
	48-16	35	34	33
	48-17	30	31	34
	48-18	32	40	48

[a] MC data were collected using an electrical-resistance-type meter with 3-in.-long insulated probe pins; readings in excess of ~30% are less reliable.

[b] Locations are as noted in Figure 16.

[c] Locations are as noted in Figures 12 and 13.