Role of nondestructive evaluation in the inspection and repair of the *USS Constitution*

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Abstract

The USDA Forest Service, Forest Products Laboratory, contributed to the development of an inspection methodology to evaluate the condition of fasteners and the general condition of the wood on the oldest floating commissioned ship in the U.S. Navy.

Introduction

The USS Constitution, known as "Old Ironsides," is the oldest floating commissioned ship in the world and still a part of the U.S. Navy. Launched on October 21, 1797, the ship is currently in drydock, being prepared for the 200th anniversary of her launching (Fig. 1). Personnel from the U.S. Navy responsible for maintaining the ship have investigated a variety of nondestructive testing techniques to assess the condition of its wood.

These tests ran the gamut from signs of deterioration observed through visual inspection to instrumented probes and advanced chemical analyses. Radiography and ultrasonic techniques were used to assess the condition of copper pins used as fasteners. Stress-wave nondestructive evaluation (NDE) techniques were used to locate areas of degradation in the wood.

Visual inspection

An extensive visual inspection of the ship was conducted at various stages of the ship's history. One of the most significant observations was the ship's continued "hogging" or "drooping" at the bow and stern. Based on visual observations, an assessment of the shape of the ship's keel was conducted (19). Prior to the current rehabilita-

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This article is a minor revision of a paper previously published in March 1996 as "Inspection of *USS Consitution*–an application of stress wave NDE," for inclusion in the book *ASTM Special Technical Publication: Wood Structures: A Global Forum on the Treatment, Conservation, and Repair of Cultural Heritage.* Also published in the International Society for Optical Engineering proceedings, December 1996, and in the APT Bulletin, the *Journal of Preservation Technology,* Vol. 29(2), 1998.

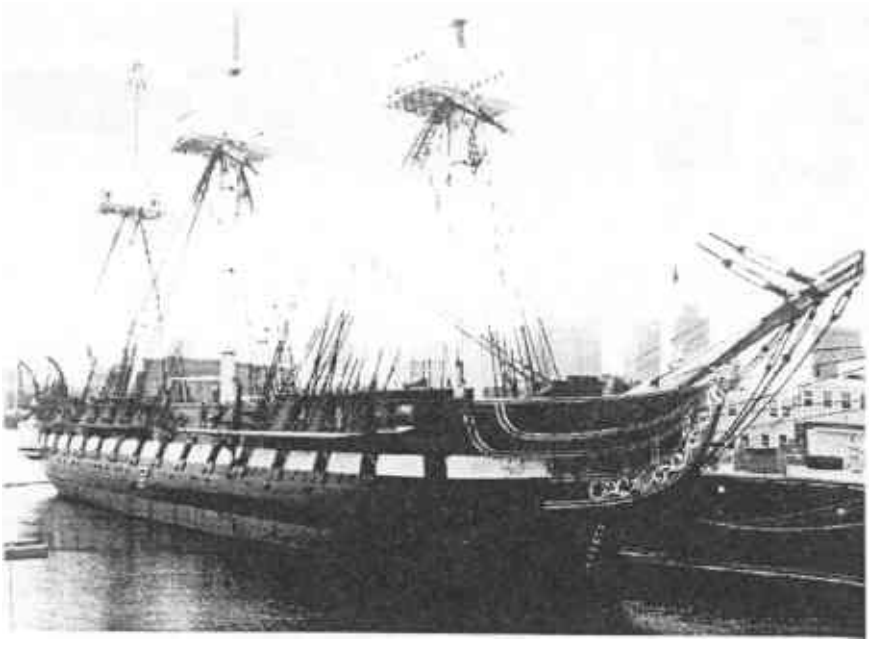

Figure 1. –*USS Constitution.*

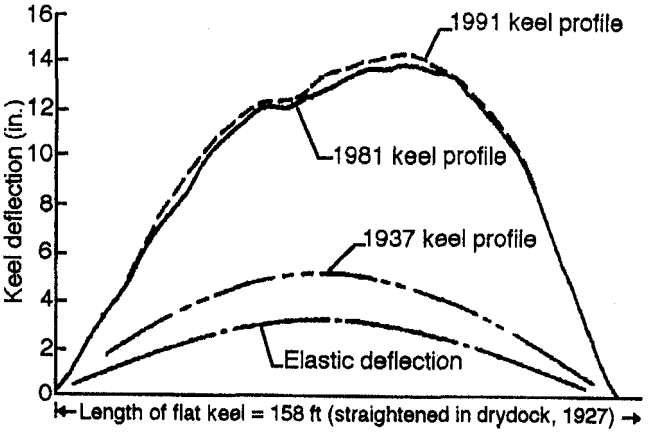

Figure 2.–*Deflection profile of ship.*

tion, the overall deflection of the ship as a result of hogging was approximately 15 inches. It was most important to examine the ship's overall deflection as a function of time (Fig. 2). Note the significant change in the deflection during the past 60 years.

Ultrasonic inspection of fasteners

Ultrasonic NDE tests were performed on the copper pins used to fasten the ship's large timber members together to determine their structural integrity. An ultrasonic pulse was transmitted via a transducer into the end of individual pins. If the pin was free of defects or deterioration, the pulse reflected off the other end of the pin. Secondary pulses were observed in partially deteriorated pins. Pin effects, such as fractures and deep pits, characteristically yielded well-defined secondary pulses and spikes in the received signals. Copper alloy pins often fail from the effects of various forms of corrosion, and the condition was readily identified in distinctive scatter characteristics of the ultrasonic pulse. This technique was used to inspect 263 pins in one week. Eighty-five percent of those inspected were classified as being in satisfactory condition. The remaining 15 percent required monitoring, and a small percentage (2%) required replacement (1 1).

Radiographic imaging

More than 300 radiographs of the copper pins were taken. These radiographs showed pin detail, and when combined with the ultrasonic inspection, provided detailed information on the conditions of the pins (1 1).

Stress-wave inspection of wood members

Stress-wave NDE techniques are used frequently to inspect large timber structures (14). A wide range of structures has been evaluated with these techniques, including bridges, piers, sports stadiums, utility poles, cooling towers, large testing structures, and residences. As an

introduction to the stress-wave technique, a schematic of the stress-wave concept for detecting deteriorated areas within a rectangular wood member is shown in Figure 3.

A stress wave is induced by striking the member with an impact device instrumented with an accelerometer that emits a start signal to a timer. A second accelerometer is coupled to the member and responds to the leading edge of the propagating stress wave sending a step signal to the timer. The elapsed time for the stress wave to propagate between the accelerometers is displayed on the timer. The underlying premise of this technique is that the speed, and hence the transmission time, at which a stress wave travels through a wood member is indicative of the condition of the member.

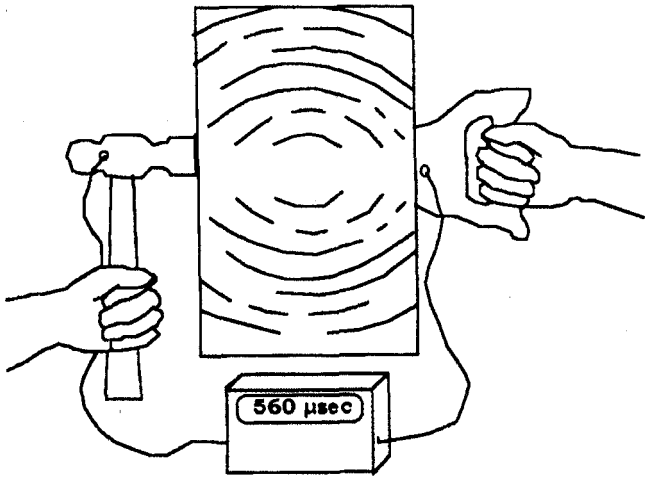

Figure 3.–*Test setup used to locate deteriorated member.*

For example, it has been shown that a stress wave travels through deteriorated wood at speeds that are significantly slower compared to sound wood. This technique has proven to be an effective method for locating large, degraded areas in timbers. Table 1 summarizes published applications of these techniques for locating deteriorated regions in timbers. Note that previous efforts were aimed at locating degraded areas in softwood timbers. No information was found on the use of these techniques for assessing degradation in hardwood timbers. In addition, limited baseline information exists on speed of stress-wave transmission values for hardwood species (Table 2).

Smulski (1 7) reported on speed of stress-wave transmission values parallel to the grain for sugar maple, yellow birch, white ash, and red oak. Armstrong et al. (1) determined speed of stress-wave transmission values, both parallel and perpendicular to the grain for birch, yellow poplar, black cherry, and red oak. McDonald (1 0) measured speed of stress-wave transmission for three hardwood species (beech, hickory,

Table 1.–*Summary of research on use of stress-wave technique for decay detection in timber structures.*

Reference	Type of structure	Type of wood product	Test procedure	Analysis
Volney (1 8)	Bridge	Douglas-fir, glulam, creosote pressure treated	Speed of stress wave perpendicular to grain, across laminations at 1-foot transmission	Sound wood: 390 µsec./ft. Moderate decay: 557 µsec./ft. Severe decay: 741 µsec./ft.
Ross (1 3)	Football stadium	Douglas-fir, solid sawn, creosote pressure treated	Speed of stress wave transmission perpendicular to grain, inspected in vicinity of connections	Sound wood: 260 µsec./ft. Incipient decay in center of members: 389 µsec./ft. 1.5-in.- (0.04-m-) thick shell of solid wood: 649 to 778 µsec./ft. Decayed member: >1300 µsec./ft.
Hoyle and Pellerin (13)	School gymnasium	Douglas-fir, glulam arches	Speed of stress wave transmission perpendicular to grain, inspected in vicinity of end supports	Sound wood: 133 µsec./ft. Decayed wood: 267 µsec./ft.

Table 2.–*Summary of research on speed of stress-wave transmission values for various species of sound wood.*

Reference	Species	Moisture content	Speed of stress-wave transmission parallel to grain		Speed of stress-wave transmission perpendicular to grain	
		(% ovendry)	(ft./sec.)	(µsec./ft.)	(ft./set.)	(µsec./ft.)
(17)[a]	Sugar maple	12	12,790–16,820	(78–59)		
	Yellow birch	11	14,270–18,020	(70–55)		
	White ash	12	13,000–16,680	(77–60)		
	Red oak	11	12,440–16,280	(80–61)		
(1)[a]	Birch	4–6	17,090 (15,384–18,800)	58 (65–53)	4,720 (4,5894,851)	212 (218–206)
	Yellow poplar	4–6	17,910 (16,930–18,890)	56 (59–53)	4,920 (4,592–5,248)	203 (218–190)
	Black cherry	4–6	16,900 (15,980–17,820)	59 (63–56)	5,020 (4,758–5,282)	199 (210–189)
	Red oak	4–6	16,530 (14,430–18,630)	60 (69–54)	5,410 (5,082–5,738)	185 (197–174)
(2)[a]	Several	11	16,000–19,700(62–51)			
(9)[a]	Red oak veneer	12	10,800–14,400 (92–69)			
(7,8)[a]	Several species		12,000–17,100 (83–58)			
(3)[a]	Stika spruce clear 2 by 4s	10	19,400 (52)			
	Southern pine clear 2 by 4s	9	16,800 (60)			
(4)[a]	Douglas-fir clear 2 by 8s	10	16,200 (62)			
(5)[a]	Southern pine clear 2 by 2s	10	17,000 (59)			
	Southern pine knotty 2 by 6s	10	16,800 (60)			
(16)[a]	Douglas-fir	12			3,000–5,260	333–190
(13)[b]	Douglas-fir	11			3,854–5,494	259–182
(6)[c]	Douglas Fir	--			7,500	133
(12)[d]	Southern pine	9	16,390–19,231 (61–52)			
(15)[e]	Northern red white oak	Green			4,464 < 2,500	224 > 400

[a] Laboratory study.
[b] Inspection of college football stadium.
[c] Inspection of gymnasium.
[d] Field study of decay.
[e] Laboratory study of bacterially infected lumber.

and red oak) in the longitudinal, radial, and tangential directions.

Many timbers in the *USS Constitution* are from live oak, a hardwood species. Consequently, baseline information on speed of stress-wave transmission in live oak was needed before using the stress-wave technique. Thus, a series of laboratory experiments was conducted to determine the baseline speed for live oak specimens prior to inspecting the ship.

To determine speed of stress-wave transmission values parallel to the grain, 80 live oak spec-

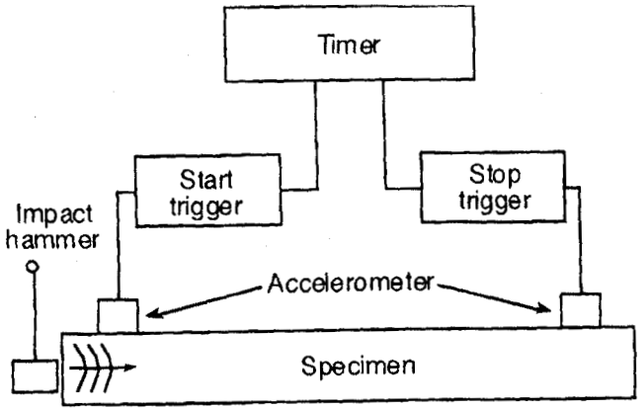

Figure 4.–*Test setup used to establish speed of stress-wave transmission parallel to grain in live oak specimens.*

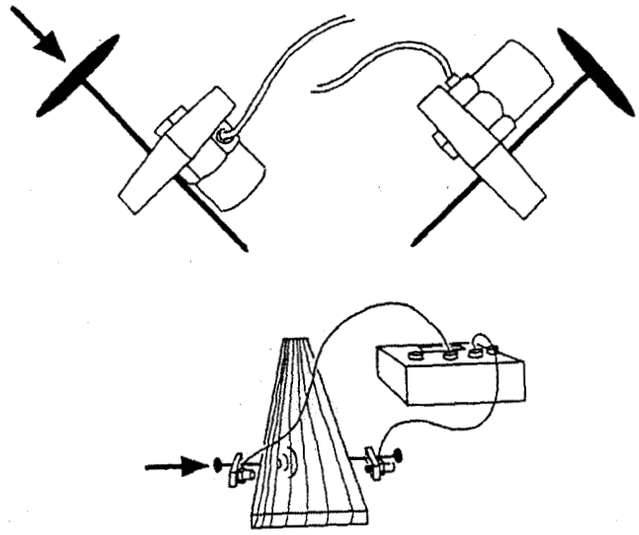

Figure 5.–*Test set-up used to measure speed of stress-wave transmission perpendicular to grain in live oak specimens.*

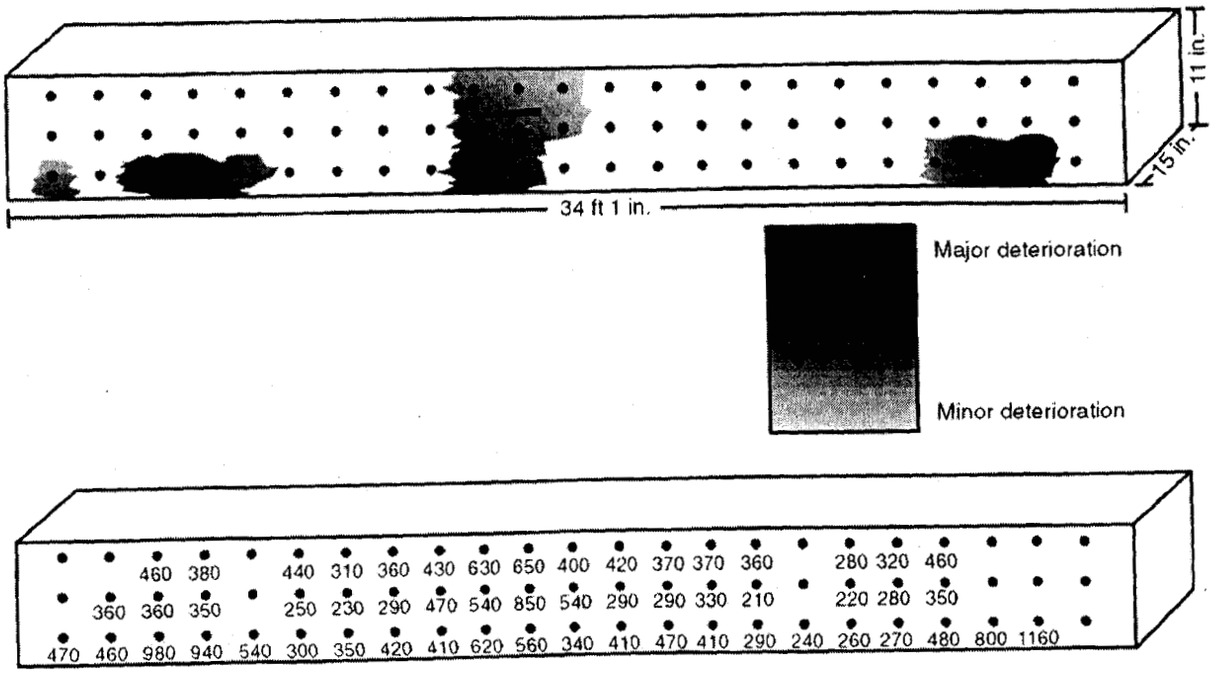

Figure6.–*A beam removed from the USS Constitution. Note the significantly lengthy transmission times in regions containing deterioration.*

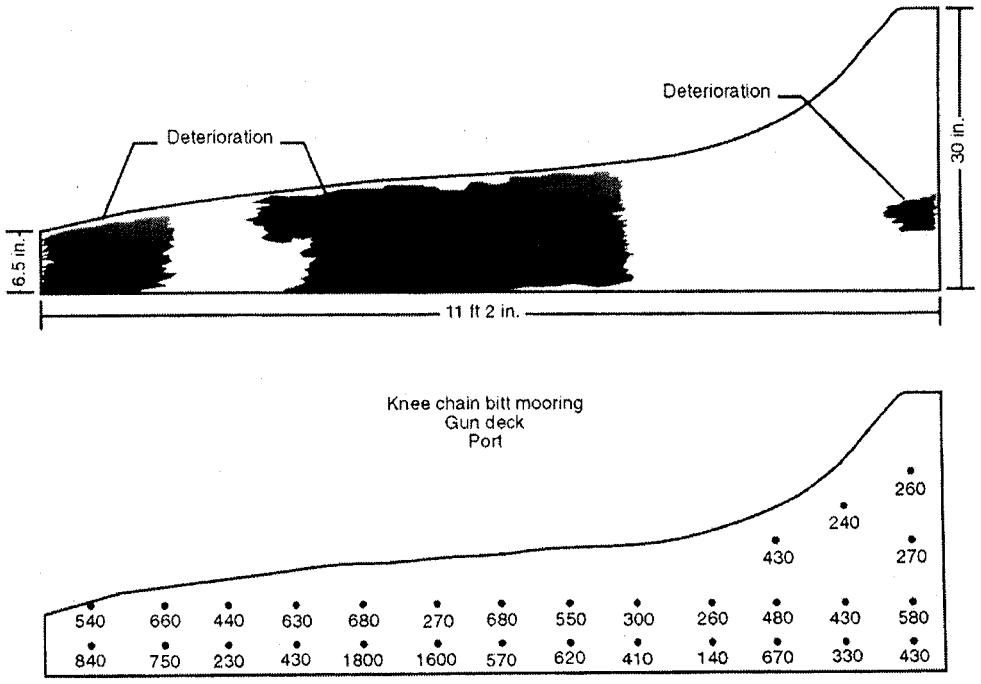

Figure 7.–*Knee chain bitt mooring from the* USS Constitution. *Note the difference in stress-wave transmission time and values of 260* µ*sec. observed in sound wood. Deteriorated wood yielded values in excess of 600* µ*spec.*

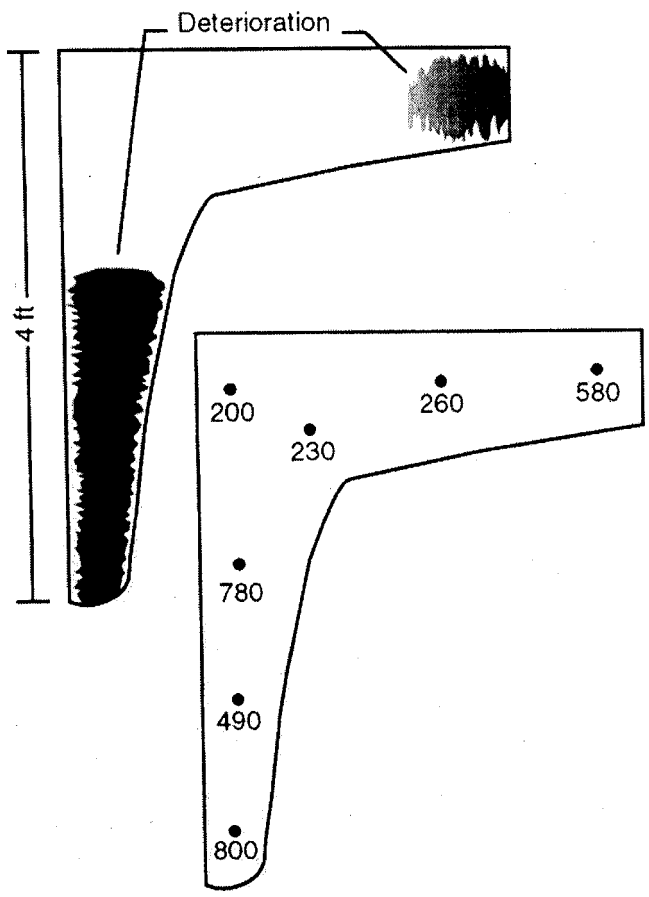

Figure8.–*A knee brace removed from the* USS Constitution.

imens measuring 1/2 by 3/8 by 12 inches (0.01 by 0.01 by 0.30-m) were tested using the experimental setup shown in Figure 4. All specimens were conditioned to approximately 12 percent equilibrium moisture content. An average value of 105 µsec./ft. (9,524 ft./sec.) was found. Values for these specimens ranged from 71 to 151 µsec./ft. (6,622 to 14,085 ft./sec.).

To determine the speed of stress-wave transmission values perpendicular to the grain, 20 live oak specimens measuring 5 by 12 by 12 inches (0.1 by 0.3 by 0.3 m) were tested using the setup illustrated in Figure 5. An average value of 278 µsec./ft. (3,597 ft./sec.) was found. Values for these specimens ranged from 2 10 to 476 µsec./ft. (2,101 to 4,762 ft./sec.).

All deck beams (four decks of approximately 32 beams each), various knees, the stern post, the stem keelson, and the keel were examined using the setup illustrated in Figure 2. Baseline stress-wave transmission times for sound live oak were calculated for the thickness of various members. Significantly lengthy transmission times indicated the presence of deterioration.

Figures 6 through 9 illustrate the results. Note that the numbers on the drawings represent the stress-wave transmission time for that particular point in the member. Significantly longer

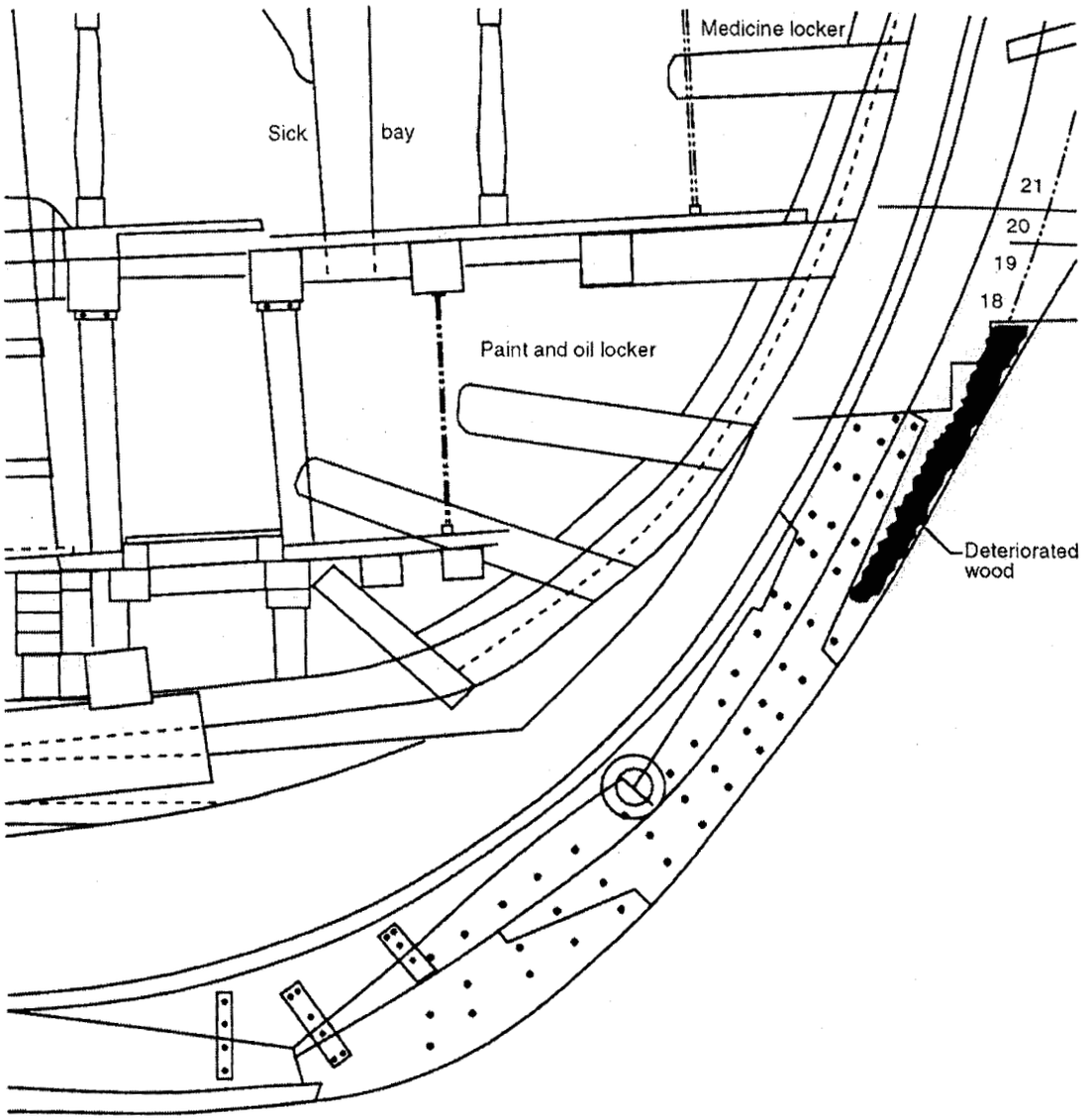

Figure 9.–*Stem from USS Constitution.*

transmission times were indicative of deteriorated wood. Inspection of these members after they were removed from the ship revealed that the severity of degradation corresponded to increases in transmission times. This finding is in agreement with previously reported results.

Conclusions

A variety of nondestructive evaluation techniques was used in the inspection of the *USS Constitution.* Visual examination, radiography, and ultrasonic techniques were used to assess the condition of the fasteners. Stress-wave nondestructive evaluation techniques were used to successfully locate deteriorated wood in the *USS Constitution.* A stress wave was induced in the member in question, and the time it took to flow through the member, perpendicular to the grain, was monitored. Significantly longer transmission times were observed when deteriorated wood was present.

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Proceedings of the

Eleventh International Symposium on Nondestructive Testing of Wood

September 9–11, 1998
Madison, Wisconsin

Sponsored by
Washington State University
College of Engineering and Architecture
Wood Materials and Engineering Laboratory
Dept. of Civil and Environmental Engineering
Conferences and Institutes
Pullman, Washington

and

USDA Forest Products Laboratory
Madison, Wisconsin

Proceedings published by the Forest Products Society
Madison, Wisconsin
1999