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Condition Assessment of the Wooden Mast of Historic Schooner *Grace Bailey*

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Citation

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Abstract

On October 9, 2023, the main mast of the historic schooner *Grace Bailey* unexpectedly snapped at about two-thirds of its height and fell onto the deck, killing one passenger and injuring three others. The United States Coast Guard promptly initiated a formal investigation into the cause of the mast's sudden failure. At the request of the Coast Guard, the U.S. Department of Agriculture, Forest Service, Forest Products Laboratory (FPL) conducted an on-site evaluation of the broken mast on December 19, 2023. The inspection used nondestructive testing methods and included visual analysis, stress wave scanning, resistance micro-drilling, and fungal identification at FPL. Severe decay was identified from stress wave transmission measurements taken between 26 and 56 ft above the mast base in the bow-to-stern axis. Suspect wood ranged from 20 to 26 ft and from 56 to 58 ft along the same axis. Along the starboard-to-port axis, suspect wood ranged from 24 to 56 ft, with decay at 37 to 38 ft and severe decay at 45 ft. Results from follow-up resistance micro-drilling tests paralleled those obtained from stress wave testing. Both stress wave scanning and resistance micro-drilling indicated the presence of severely deteriorated wood. Brown rot was visually observed on samples of decayed mast, and laboratory examination of the samples indicated the presence of the polypore *Antrodia xantha*. The findings from these tests provide detailed data on the mast's physical condition and help pinpoint potential factors that contributed to its catastrophic failure while in service.

Keywords: inspection, decay, nondestructive testing, wooden mast, schooner, ship

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Cover photo: Undated photograph of schooner *Grace Bailey*. United States Coast Guard photo.

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Introduction

The *Grace Bailey* is a two-masted schooner built in 1882 in Patchogue, New York, one of five surviving two-masted, wooden-hulled schooners that were once the most common vessels in the American coasting trade. Named after the daughter of the owner, Edwin Bailey, the *Grace Bailey* was originally built to transport lumber from southern ports to Patchogue for shipbuilding. In 1906, the schooner was rebuilt and renamed after Bailey's granddaughter, Martha, and sailed until 1990 under her nickname, Mattie (Dean and Mohney 1990). According to the ship's website (https://www.sailgracebailey.com/history-grace-bailey), the *Grace Bailey* was actively engaged from its launch through 1914 in coastal and foreign trade and made multiple voyages to the West Indies. Under the command of Captain Seymour Ketcham, much of its operations involved transporting lumber from South Carolina to Georgia. The ship was restored in 1990 and returned to its original name. The *Grace Bailey* was declared a National Historic Landmark in 1992.

The *Grace Bailey* measures 118 ft in length and has a gross tonnage of 58. It is constructed with white oak framing and planking and features a deck made of longleaf yellow pine. On October 9, 2023, *Grace Bailey* was located a mile east of Rockland, Maine, carrying 33 passengers on a return voyage from a 5-day fall foliage cruise. The 75-ft main mast broke at about two-thirds of its height, falling down onto the deck along with the gaff supporting the mainsail. The incident resulted in the death of one passenger and injuries to three others (Molyneaux 2023). The United States Coast Guard launched a formal investigation into the sudden and catastrophic failure of the wooden mast on this historic schooner and issued a report of its findings (Incident Investigation Activity #7836612).

Scope of Work

Coast Guard investigators William Wallen and Lieutenant [redacted] contacted scientists at the U.S. Department of Agriculture, Forest Service, Forest Products Laboratory (FPL), to explore whether nondestructive testing (NDT) methods could have detected heart rot before the structural failure occurred. In response to a request from the Coast Guard, FPL scientists traveled to Rockport, Maine, and from December 18 to December 20, 2023 conducted an on-site evaluation of the *Grace Bailey* main mast using NDT methods commonly applied to timber structures. The goal of the assessment was to provide detailed, quantitative information about the current physical condition of the mast and to identify potential factors that contributed to its failure during service.

Mast in Question

The *Grace Bailey* masts are made of Douglas-fir (*Pseudotsuga menziesii*), a species native to western North America and commonly used in various structural applications. The main mast and foremast were produced from 70-ft and 68-ft solid timber, respectively, both milled to an approximate diameter of 18 in. at the base and 16 in. at the top. The inspection records indicate that the foremast received scarf repairs in 2013 and 2014, and the main mast received scarf repair in 2014. Repairs were made with dry Douglas-fir to match the original masts. The on-site investigation was primarily focused on the broken main mast, which had been removed and stored in a facility in Rockport, Maine.

Inspection Methods

Inspection methods used in this investigation included visual inspection, stress wave scanning, resistance micro-drilling, and fungal identification. Stress wave scanning and resistance micro-drilling are advanced nondestructive testing techniques that assess the internal physical conditions of wooden structures (FPL 2000, White and Ross 2014). Prior to the investigation of the *Grace Bailey*, the inspection team had applied these NDT methods to evaluate other historic structures, including wooden ships: the USS *Constitution* (Ross et al. 1996), the *C.A. Thayer*,[1] the *Highlander Sea* (Wang and Wacker 2006a), the U.S. Brig *Niagara* (Wang and Wacker 2006b), the *Wapama* (Wang et al. 2008), and the *Minnehaha*.[2] These techniques are widely used by inspection professionals around the world for evaluating a range of historic artifacts and timber structures. Following is a brief overview of each technique used in the evaluation of the *Grace Bailey* mast.

Stress Wave Scanning

Stress wave scanning (stress wave/sound transmission) technique has been used successfully to detect decay in wood structures. The concept of detecting decay using this method is that stress wave propagation is sensitive to the presence of degradation in wood. The underlying premise is that stress waves travel faster through sound and high-quality wood than through deteriorated or low-quality wood. The time of flight (i.e., transmission time) of the stress wave is typically used as a predictor of the physical condition of the wood. By measuring the time of flight of a stress wave travelling through a wood member (perpendicular to the grain), the internal condition of the member can be determined. White and Ross (2014) and FPL (2000) provide detailed information on the principles of this technique, guidelines for use and interpretation, commercially available equipment, and examples of use.

Resistance Micro-Drilling

Resistance micro-drilling is a quasi-nondestructive inspection technique. The tool uses an instrumented drill that measures the driving force and torque of a specialized drill bit. The drill bit can vary in length from 8 to 14 in.; the head is a paddle bit with a ⅛-in.-wide head and a 1⁄16-in.-diameter shaft. The drill is positioned against the edge of the inspected timber. Once activated, the drill pushes the bit forward while drilling. The force necessary to push the drill forward and the torque necessary to turn the bit are recorded alongside the extension of the bit. Decreases in pushing force, torque, or both indicate low strength wood or voids. Because resistance micro-drilling can reveal the relative density change along the drill path, it is typically used to diagnose the internal condition of structural timbers. White and Ross (2014) and Brashaw et al. (2005) provide detailed information on the use of resistance micro-drilling.

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[1] Report on the inspection of keel and mizzenmast on the *C.A. Thayer*, 2001, prepared by the U.S. Department of Agriculture, Forest Service, Forest Products Laboratory for the U.S. Department of the Interior, National Park Service, San Francisco Maritime National Park, by R.J. Ross, J. Kirchner, X. Wang, and J.W. Forsman.

[2] Condition assessment of the steamboat *Minnehaha*, 2009, prepared by the Natural Resources Research Institute, University of Minnesota Duluth, for the Museum of Lake Minnetonka, Excelsior, MN, by B.K. Brashaw, X. Wang, R.J. Vatalaro, and R.J. Ross.

Inspection Procedures

On-site inspection of the main mast was conducted on December 19, 2023, at a covered storage facility in Rockport, Maine. The general condition of the mast was inspected visually and documented in multiple photos. To detect the presence of internal decay, stress wave transmission measurements were performed at a series of cross sections of the mast using a Fakopp Microsecond Timer unit (Fakopp Kft, Sopron, Hungary). Measurements were taken every foot in both horizontal and vertical cross-grain directions with the mast laid horizontally across two supporting sawhorses. The diagram in Figure 1 shows the stress wave data collection points in the mast. Figures 1I through 1L show the sensor probes inserted into the mast at two opposing sides to measure the time of flight. The stress wave transmission test required access to two opposite sides of the mast for attaching sensor probes. During the stress wave transmission measurements, the diameter of the mast was measured at several locations along the mast height. The cross section of the mast was circular for most of the length and transitioned to square for the top 8 ft. The mast was broken between 45 and 53 ft; therefore, no stress wave data were collected in that region.

Following the stress wave transmission measurements, cross-grain resistance micro-drilling tests were conducted to verify the stress wave measurements. An IML-RESI PD400 drilling tool (IML North America, LLC, Meredith, NH, USA) was used at three locations: 21, 25, and 34 ft from the base. Locations of resistance drilling tests are labeled Res. Drill in Figure 1.

In addition to the physical tests, decayed wood samples were collected from five different locations in the mast, stored in plastic bags, and brought back to the Forest Products Laboratory for fungal identification. The yellow, porous fungus present on the Douglas-fir mast was visually identified using fungal identification keys by FPL staff.

Observations and Findings

Visual Observations

Figure 1 shows photographs of mast features and a diagram giving the approximate locations. Full-size images of these photographs are provided in the Appendix. The mast was broken approximately 20 ft from the top. Extensive, deep checks were observed on many sections of the mast. Surface deterioration from fungal decay was observed at 5 and 63 ft above the mast base. Some areas near the location of the failure indicated that probing tests using a pocketknife were conducted during the inspection after the incident.

The broken top of the mast is shown in Figure 1A. The fracture surface is shown in Figures 1B through 1F. Evidence of fungal decay is present as the white coloration in Figures 1B, 1D, and 1F. Figures 1E and 1F show regions of brash failure (i.e., a sudden, brittle break with little or no splitting) and cubical fracturing (i.e., a crack pattern in which the wood breaks into cube-like blocks). Both are evidence of fungal decay in wood.

Figures 1G, 1H, and 1I show inspection holes created prior to the FPL inspection. The holes allowed access to the interior of the mast, where extensive internal decay was observed. Fungal decay, evidence of brash failed wood, and cubical wood remnants were visible in the three locations of the inspection holes.

Figure 1J shows the first evidence of suspect wood at approximately 21 ft from the base of the mast, which is in the middle of the scarf joint from the 2014 scarf repair. Figure 1K shows the mast at deck height in visually sound condition. Figure 1L shows the mast area 5 ft above the base where localized surface deterioration is visible.

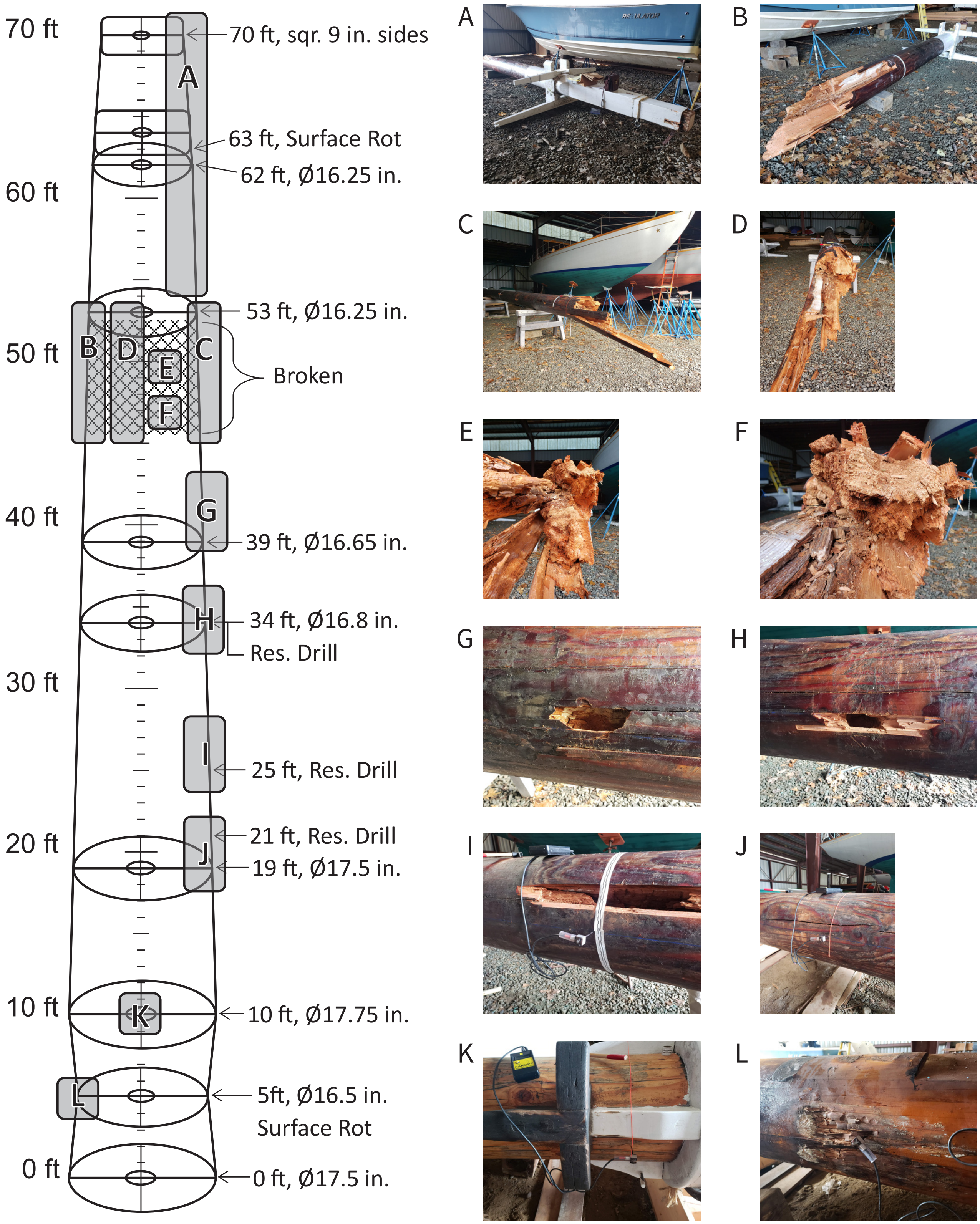

Figure 1.—Diagram of the main mast of the *Grace Bailey* and photographs documenting the features observed along the mast. The location of each photo is identified in the diagram. A: broken top of the mast; B, C, D, E, F: fracture surface; G, H, I: examination holes created prior to inspection by the Forest Products Laboratory; J: first observable internal decay from stress wave scanning tests; K: mast at deck height; L: mast 5 ft above the base showing surface deterioration. Larger photographs are provided in the Appendix. Forest Service photos by Xiping Wang.

Results of Stress Wave Transmission Measurements

Figure 2 shows the distribution of stress wave transmission time or time of flight (ToF), expressed in microseconds (µs), and mapping of the physical condition for the failed mast. The transmission time across the grain is normalized by the distance between the starting and stopping probes, yielding a common unit of µs/ft for ToF. Normal range of sound wood is less than or equal to 200 µs/ft; suspect wood is more than 200 and less than 300 µs/ft; above 300 µs/ft is indicative of decayed wood. Figure 2 shows the ToF values by color along the length of the mast.

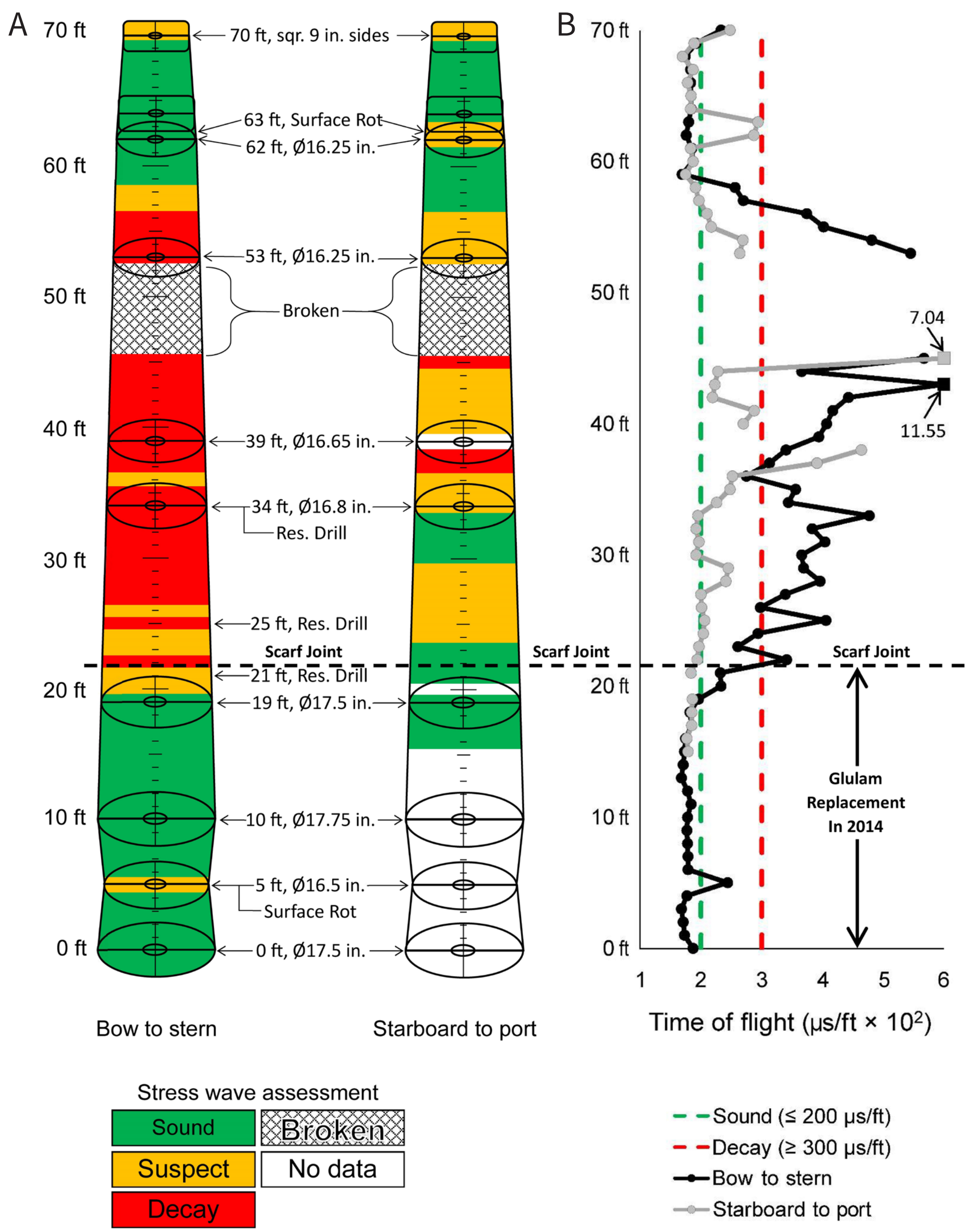

Figure 2.—Mapping of physical condition of the main mast of the *Grace Bailey*. A: the mast condition as indicated by stress wave transmission time for the directions of bow to stern and starboard to port. B: time of flight (ToF) values. Values between 200 and 300 µs/ft are assumed to be suspect.

Measurements were taken at cross sections every 1 ft of mast length and in two perpendicular directions: from bow to stern and from starboard to port. Overlaid green shading indicates sound wood, yellow shading indicates suspect wood, and red shading indicates decayed wood. A chart of the numerical ToF values and thresholds for sound and decayed wood are also shown in Figure 2. Some locations had ToF values more than 600 μs/ft, indicating advanced decay with severe structural degradation; the locations of highest ToF were located just above and just below the broken region of the mast, supporting the hypothesis that the mast broke in the region of worst decay. Severe decay was identified from the stress wave transmission measurements taken between 26 and 56 ft above the mast base in the bow-to-stern axis. Suspect wood ranged from 20 to 26 ft and 56 to 58 ft along the same axis. Along the starboard-to-port axis, suspect wood ranged from 24 to 56 ft, with decay at 37 to 38 ft and severe decay at 45 ft.

Results of Resistance Micro-Drilling Tests

Figure 3 shows an idealized cross section of a timber pole with an overlay of a resistance drill output. The left side of the figure depicts good wood characterized by visible, distinct peaks corresponding to annual rings. The red shaded area on the right side depicts decayed wood. In the decayed wood, both the torque and the pushing force are very low when compared to the good wood. The yellow shaded area near the center is a suspect area. The height and distinctiveness of the peaks are decreased but still visible.

Coast Guard and FPL personnel performed resistance drilling of the mast independently. The Coast Guard took resistance drill measurements every 2 ft starting at the deck height along the mast and continuing until just below the cross bar. FPL took resistance drill measurements at three locations along the mast: 21, 25, and 34 ft based on the stress wave measurements. The FPL measurements at 21 ft were compared to the Coast Guard measurements at 20 ft. Both measurements showed areas of rot starting at or about 1.5 in. from the surface and extending to approximately 6 in. below the surface. The comparison showed good agreement between both sets of measurements. Variations were attributed to differences in drilling locations and difference in settings for the tool used. Figure 4A shows Coast Guard measurements at 20 ft; Figure 4B shows FPL measurements at 21 ft.

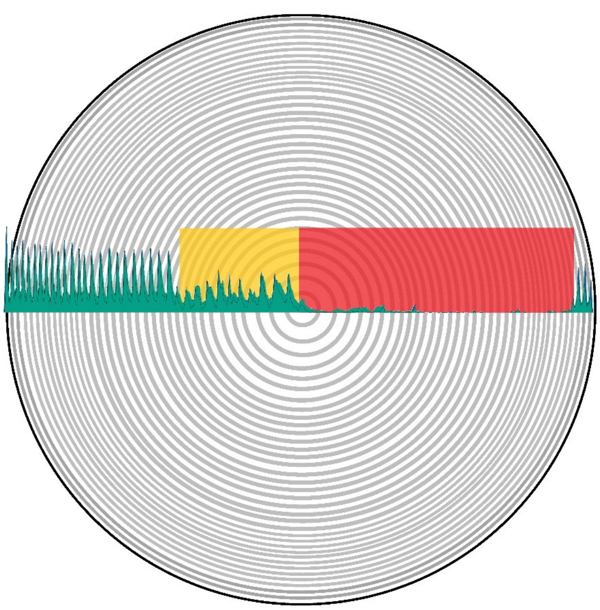

Figure 3.—Idealized timber pole cross section with resistance drill torque and pushing force overlay. Sound wood is visible on the left side with tall, distinct peaks corresponding to denser annual rings. Decayed wood appears as red on the right side and has no distinct peaks. Suspect wood appears as yellow toward the center and has visible peaks that are lower in magnitude and less distinct than sound wood.

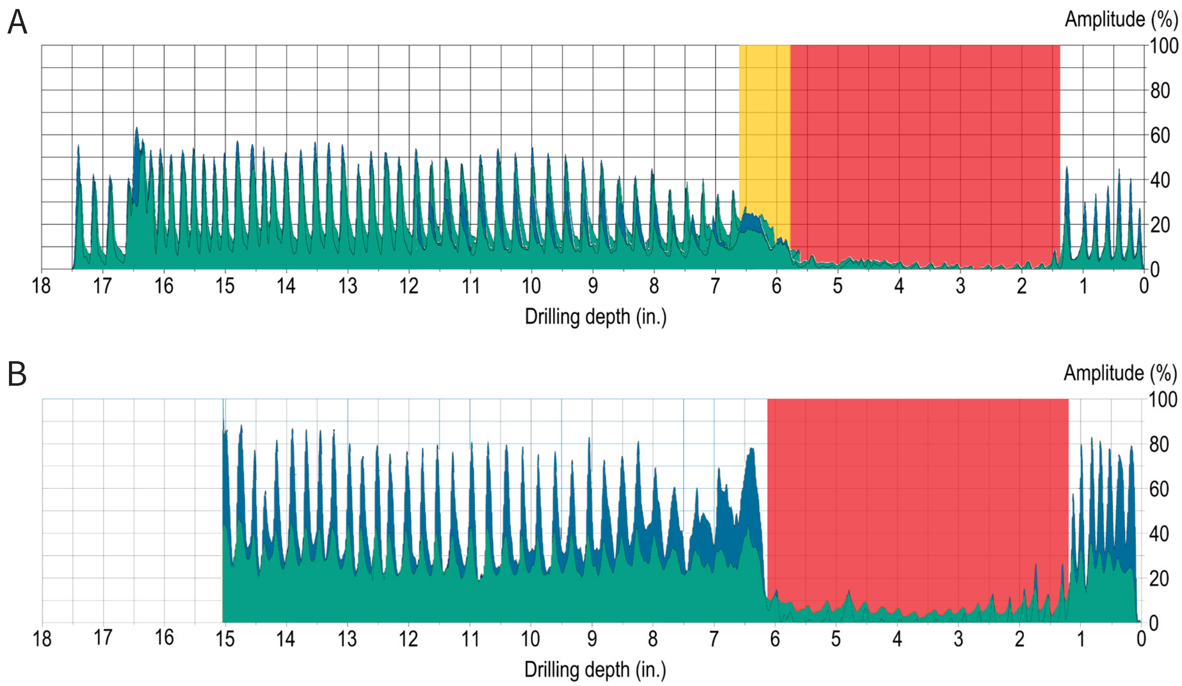

Figure 4.—Comparison of the U.S. Coast Guard (USCG) and Forest Products Laboratory (FPL) resistance drilling measurements of the *Grace Bailey* mast using the IML-RESI tool (IML North America, LLC, Meredith, NH, USA). A: USCG measurements at 20 ft height of the mast. B: FPL measurements at 21 ft height of the mast. Both measurements show decay starting at or above 1.5 in. from the front of the mast and extending radially to approximately 6 in.

The resistance drilling results were then compared to the time of flight measurements. Figures 5A and 5B show conceptualized cross sections of the mast. Areas of decay and suspect wood are shaded in red and yellow, respectively, based on the Coast Guard resistance drilling data. Under each image is the height of the measurement, the diameter of the mast at that location, and the ToF along the bow-to-stern (BN) axis and the starboard-to-port (SP) axis. Note that the height values listed are the distance from the base of the mast. The Coast Guard measured height as the distance from the deck. As a result, the resistance drilling heights shown in this report have values 10 ft higher than those in the Coast Guard's report. The conversion here is for consistency among the report figures. It is apparent that a region of decayed wood is present in most of the mast height from the centerline of the mast to the edge of the mast facing the bow of the ship. As height increases, the decay extends closer to the outer shell of the mast. There are several areas of suspect wood along the SP axis of the mast, but degradation along the SP axis is noticeably lower than along the BN axis.

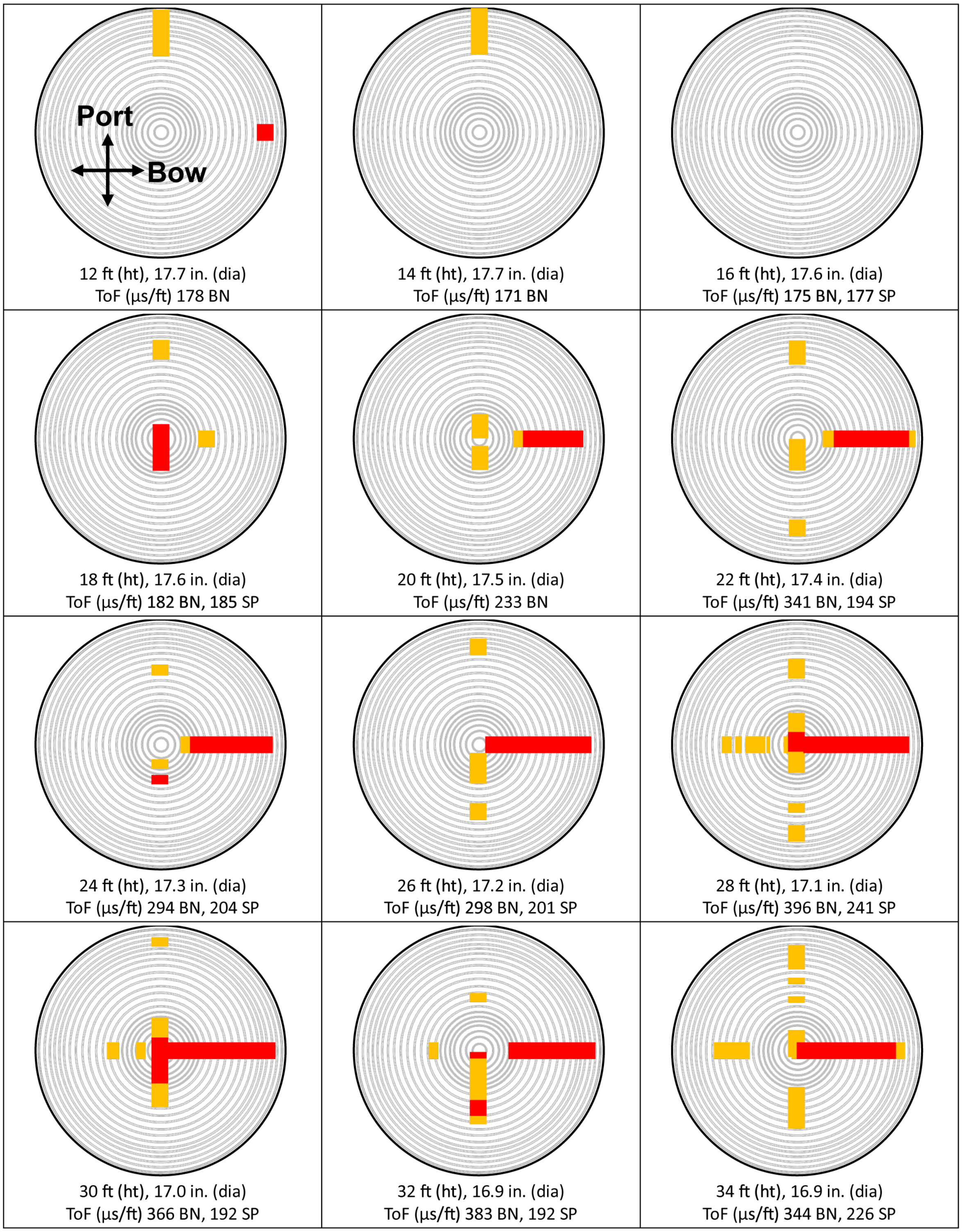

Figure 5a.—U.S. Coast Guard resistance drilling results of the *Grace Bailey* mast from 12 to 34 ft. Decayed and suspect wood are indicated by red and yellow shading, respectively. Mast diameter (dia), time of flight (ToF) across the bow-to-stern axis (BN) and across the starboard-to-port (SP) axis are given at each height.

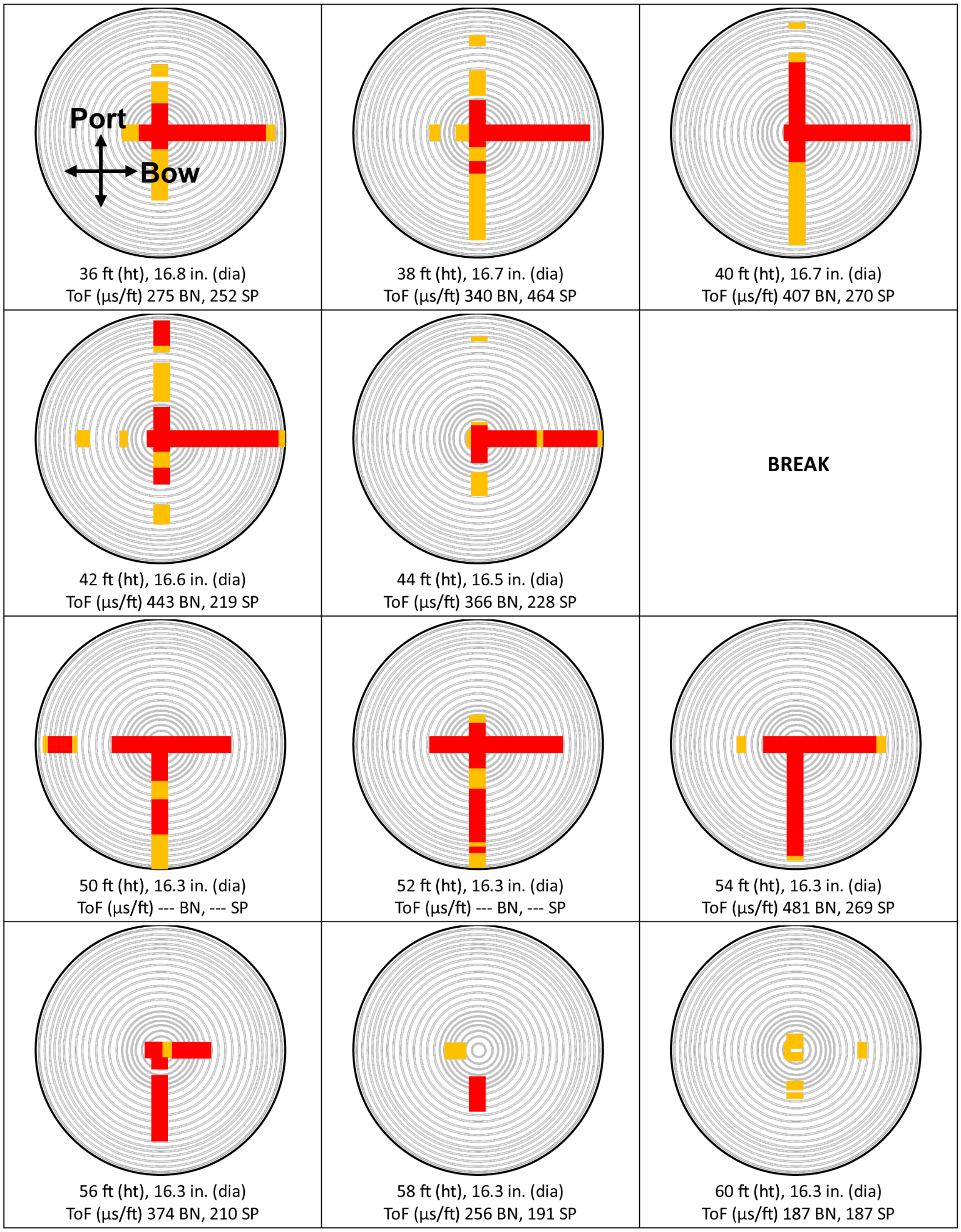

Figure 5b.—U.S. Coast Guard resistance drilling results of the *Grace Bailey* mast 36 to 60 ft. The mast broke between 44 and 50 ft. Decayed and suspect wood are indicated by red and yellow shading, respectively. Mast diameter (dia), time of flight (ToF) across the bow-to-stern axis (BN) and across the starboard-to-port (SP) axis are given at each height.

Fungal Identification

Figure 6 shows six samples of decayed wood collected from different sections of the mast. Figure 6A was collected from the mast at 47 to 48 ft (see Fig. 1F), 6B was collected at 53 ft (see Fig. 1B), 6C was collected at 36 ft (see Fig. 1H), 6D was collected at 28 ft (see Fig. 1I), and 6E and 6F were collected at 43 ft (see Fig. 1G). Brown rot decayed wood is visible in 6A, 6B, 6C, and 6D. An unknown yellow, porous fungus is visible in 6E and 6F.

The initial examination found that the unknown polypore that caused extensive brown rot decay of the mast had a citric yellow pore surface containing small pores. It was hypothesized that the polypore could be *Auriporia* (encrusted cystidia), *Laetiporus* (no clamps), *Wolfiporia* (no clamps), *Anomoporia* (monomitic with no skeletal hyphae), or *Antrodia*. Further examination showed dimitic, generative hyphae with multiple clamps and unbranching, thick-walled skeletal hyphae. *Auriporia* typically has encrusted cystidia (sterile cells viewed under the microscope); however, none were found from the unknown polypore. It was determined that the polypore belonged to the genus *Antrodia* and was likely either *Antrodia xantha*, synonymous to *Daedalea xantha*, (Fr.) A. Roy & A.B. De, or *Antrodia alpina* (Litsch.) Gilb. & Ryvarden. The Gilbertson and Ryvarden (1986) key to North American polypores lists the definitive character between the two as number of pores per mm, with 2 to 4 per mm for *Antrodia alpina* and 5 to 7 per mm for *Antrodia xantha.* The unknown specimen had frequent instances of more than 5 pores per mm, and upon comparison with herbarium specimens, the larger pores on *Antrodia alpina* herbarium specimens (two available and examined) were obvious, with frequent instances of 2 pores per mm. In contrast, herbarium specimens of *Antrodia xantha* examined had frequent instances of more than 5 pores per mm, the same range as the unknown specimen. With this information, it is highly likely the polypore that caused the brown rot was *Antrodia xantha*.

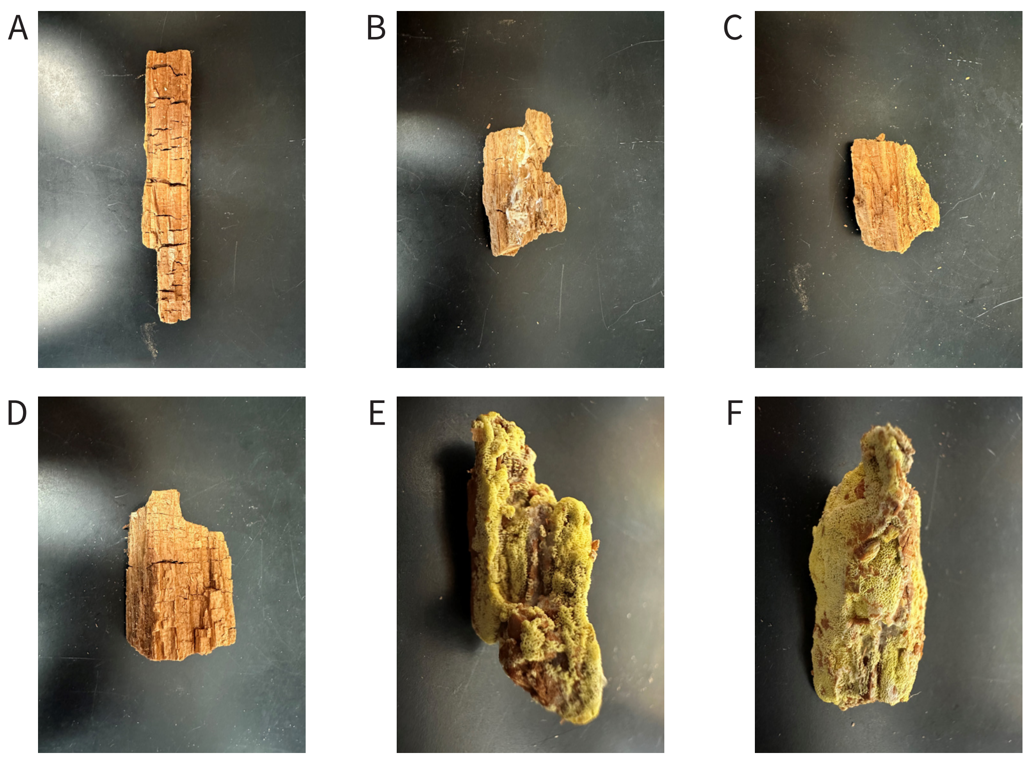

Figure 6.—Douglas-fir decayed wood samples collected from five locations of the *Grace Bailey* mast showing brown rot and yellow fungal mycelia. A: broken section at 47 to 48 ft; B: upper broken section at 53 ft; C: mast section at 36 ft; D: mast section at 28 ft; E and F: mast section at 43 ft. Forest Service photos by Katie M. Ohno.

Summary

An on-site inspection of the failed mast of the *Grace Bailey* was conducted using nondestructive testing methods. The mast broke approximately 20 ft from the top. Extensive and deep checks were observed on many locations of the mast. Severe decay was found between 26 and 56 ft above the mast base along the bow-to-stern axis. Suspect wood was identified from 20 to 26 ft and from 56 to 58 ft along the same axis. Along the starboard-to-port axis, suspect wood extended from 24 to 56 ft, with decay present between 37 to 38 ft and severe decay at 45 ft. The resistance micro-drilling tests conducted independently by the Coast Guard and FPL teams aligned with the results from the stress wave scanning test. Both the time of flight and resistance micro-drilling data indicated the presence of severely deteriorated wood in the mast. Brown rot was visually identified on decayed mast samples, and laboratory examination revealed the unknown polypore to be *Antrodia xantha*.

Effects of Deterioration on Wood Strength

The Forest Products Laboratory is frequently asked for assistance in assessing the condition of wood and wood products in historic artifacts and structures and has produced publications on the topic (Ross et al. 2017; White and Ross 2014). Deterioration in wood resulting from fungal attack results in a significant reduction in strength properties. The following summarizes fundamental research on the effects of decay on the strength properties of wood.

Toughness (Impact Bending)

Toughness (the ability of a wood member to withstand shock loading) is generally considered to be the strength property most affected in early stages of decay. Research dating to 1954 indicates that a loss of only 1 percent in weight corresponds to a toughness loss of up to 50 percent.

Static Bending Properties

Research dating to the 1930s has been conducted on modulus of elasticity, modulus of rupture, and work-to-maximum-load of wood exposed to decay in a bending mode. Reported results indicated a significant loss in modulus of rupture (strength) after wood had been exposed to decay fungi.

Other Strength Properties

Research has shown that compression strength (perpendicular and parallel to the grain), tension parallel to the grain, shear parallel to the grain, and tangential hardness are also impacted significantly by deterioration caused by decay fungi.

Acknowledgments

We would like to thank William Wallen and Lieutenant [redacted] of the United States Coast Guard for aiding with the on-site inspection and for providing the resistance drill data obtained by Coast Guard personnel. We would also like to thank John Haight, Forest Service, Northern Research Station, for his technical assistance with identifying the fungal organism present in the decayed mast.

Conversions

When you know	Multiply by	To convert to
in. (inches)	25.4	mm (millimeters)
ft (feet)	0.3048	m (meters)
µs/ft (microsecond/foot)	3.281	µs/m (microsecond/meter)

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Appendix: Photos of *Grace Bailey* Mast Taken During On-site Inspection, November 19, 2023

Figure numbers on the following pages correspond to Figure 1.

Figure 1A.—Broken top of the *Grace Bailey* mast. Forest Service photo by Xiping Wang.

Figure 1B.—Fracture surface of the *Grace Bailey* mast (upper portion). Forest Service photo by Xiping Wang.

Figure 1C.—Fracture of the *Grace Bailey* mast (lower portion). Forest Service photo by Xiping Wang.

Figure 1D.—Fracture surface of the *Grace Bailey* mast (upper portion). Forest Service photo by Xiping Wang.

Figure 1E.—Close up of fractured cross section of the *Grace Bailey* mast. Forest Service photo by Xiping Wang.

Figure 1F.—Close up of fractured cross section of the *Grace Bailey* mast. Forest Service photo by Xiping Wang.

Figure 1G.—Examination hole in the *Grace Bailey* mast (at approximately 39 ft) created prior to Forest Products Laboratory inspection and revealing internal decay. Forest Service photo by Xiping Wang.

Figure 1H.—Examination hole in the *Grace Bailey* mast (at approximately 34 ft) created prior to Forest Products Laboratory inspection and revealing internal decay. Forest Service photo by Xiping Wang.

Figure 1I.—Opening in the *Grace Bailey* mast (at approximately 25 ft) created prior to Forest Products Laboratory inspection and revealing internal decay. Forest Service photo by Xiping Wang.

Figure 1J.—Stress wave transmission test performed on the *Grace Bailey* mast at 21 ft detecting possible internal decay. Forest Service photo by Xiping Wang.

Figure 1K.—*Grace Bailey* mast at deck height. Forest Service photo by Xiping Wang.

Figure 1L.—Surface deterioration observed on the *Grace Bailey* mast at 5 ft. Forest Service photo by Xiping Wang.

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