PETER W. WITHERELL, ROBERT J. ROSS, PH.D & WILLIAM R. FARIS

Using Today's Technology to Help Preserve USS Constitution

THE AUTHORS

Peter W. Witherell *holds a B.S. degree in naval architecture and marine engineering from the University of Michigan (1974) and an M.S.E. degree from George Washington University (1978). Since 1974 he has worked for several Navy agencies as a naval architect, including: the Naval Ship Engineering Center, Naval Sea Systems Command, S.R.F. Guam, SupShip Boston, and Puget Sound Naval Shipyard Detachment Boston. His design experience encompasses surface effect ships, air cushion vehicles, floating drydocks, and amphibious ships in addition to the USS* Constitution. *His association with* Constitution *began at SupShip Boston in 1980, when he developed a maintenance manual for the ship. Since that time he has developed a finite element model to perform structural analyses on the ship, and most recentlv was the project engineer in the design of a supporting framework for the ship.*

Robert J. Ross *holds B.S. and M.S. degrees from Michigan Technological University (1978, 1981) and completed his Ph.D. in Engineering Science from Washington State University in 1984. Formerly with Metriguard, Inc. and Trus Joist Corporation, he has been in charge of the USDA Forest Service Forest Products Laboratory's (FPL) physical and mechanical testing unit since 1988. In that capacity, he oversees mechanicul testing programs involving a wide range of wood-based materials and structural components. He also leads FPL's nondestructive evaluation research efforts. and is actively involved in developing an in-place assessment method for USS* Constitution.

William R. Faris *has been active in the marine field since 1968, including four years spent with the merchant marine. From 1972 to 1976, he worked in both shipyards and boat shops and, in 1976, opened his own boat repair shop. He operated a shop until 1982, when he began employment as a marine surveyor. In 1987, he developed a successful ultrasonic inspection technique for the in-place identification of defective fasteners, and opened his own marine surveying and consulting firm in that year. His efforts for the Navy have included fastener inspections on twelve minesweepers and the USS* Constitution. *His other inspection work is primarily for insurance companies, including Lloyds of London.*

ABSTRACT

In order to retain as much of the USS Constitution's remaining original material as possible, and at the same time preserve the ship's hull form and structural integrity for the future, the Navy has conducted numerous inspections and engineering studies over the past decade. While much of this work has involved visual inspections, test borings, mechanical testing, classical naval architecture calculations, and research into past shipbuilding practices, a commeasurate amount of effort has also been directed at using today's technology to maximum advantage. This paper discusses: 1) inspecting the ship's fasteners using ultrasonic testing, 2) inspecting the ship's wooden structure using three nondestructive test methods, 3) analyzing ship deflections and general stress levels using finite element modeling on a computer, and 4) investigating the use of fiber reinforced composites to strengthen the ship.

INTRODUCTION

The USS *Constitution* was launched on 21 October 1797 and is the oldest commissioned ship afloat in the world today. She carries this distinction largely based on the fact that a portion of the ship's underwater structure is considered to be original. Included in this original material are the keel, deadwood, floors, lower planking strakes, and a number of lower frame futtocks. This material has lasted because it is water-soaked, and too wet to promote rot. Elsewhere in the ship, where wood moisture contents may vary from 15% to 40% due to intermittent wetting from rainwater or seawater, structural members decay, and original wood has been replaced during past overhauls.

In recent years, the Navy has become concerned about the material condition of *Constitution,* particularly because of the ship's continued "hogging", or "drooping" at the bow and stem. Figures 1 and 2 show how the appearance of the ship changed from 1931 to 1986, and Figure 3 shows how the shape of the keel changed during the same period. At present, the overall deflection of the ship due to hogging (primary bending) is about 15 inches. The relatively slow rate of increase in deflection that occurred during the 1981-1991 time frame (l/2-inch per 10 years vs. nearly 2-inches per 10 years

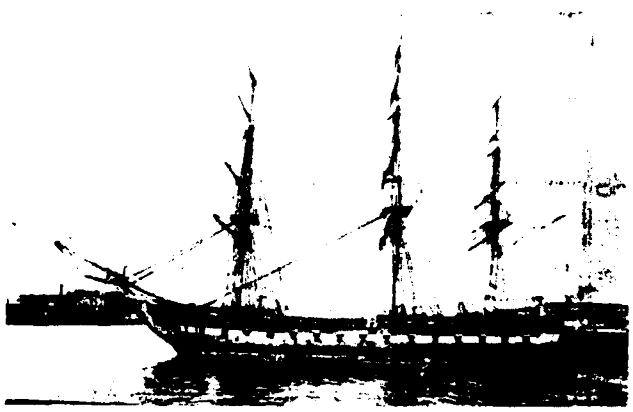

Figure 1. USS *Constitution*, not long after her 1930 undocking.

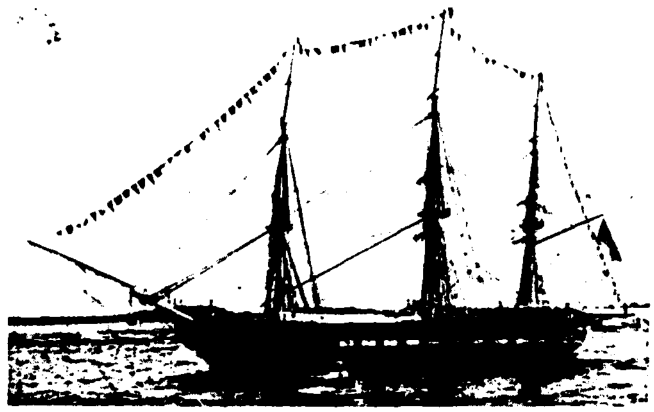

Figure 2. USS *Constitution*, during the July 4, 1986 Turnaround Cruise.

for the 1937-1981 time period) is the result of major weight shifts that were made aboard the ship in 1981.

As can be seen in Figure 3, *Constitution's* keel profile shows evidence of secondary deflections beneath the mainmast and in the vicinity of the scarf joint immediately forward of the mainmast. On the basis of primary bending alone, the keel profile would be bell-shaped and nearly symmetric. The forward skew in the keel profile and the dip in the keel beneath the mainmast suggest weakness in the two mid-keel scarf joints, where the secondary deflections are most pronounced.

While continued longitudinal deformation has been a major concern, it has not been the only one. In 1984, for example, a number of 1927 era copper drift pins were removed from inside the ship, and several were found to have crevice corrosion where they passed through the ceiling plank/frame interface. As Figure 4 shows, crevice corrosion on a copper pin is apt to occur wherever salt water enters a narrow opening to contact it. Once corrosion starts, the composition of the water within the narrow opening changes, and this change, in turn, leads to accelerated corrosion at the pin surface. Considering the effects which crevice corrosion can have on fastener strength, and the fact that the underwater structure of *Constitution* is held together by copper pins, it becomes clear that monitoring the condition of these pins is essential.

The routine maintenance and repairs which are performed on *Constitution* help to control and prevent decay but, generally speaking, do not enhance the ship's overall structural integrity, On the contrary, the increase in residual ship

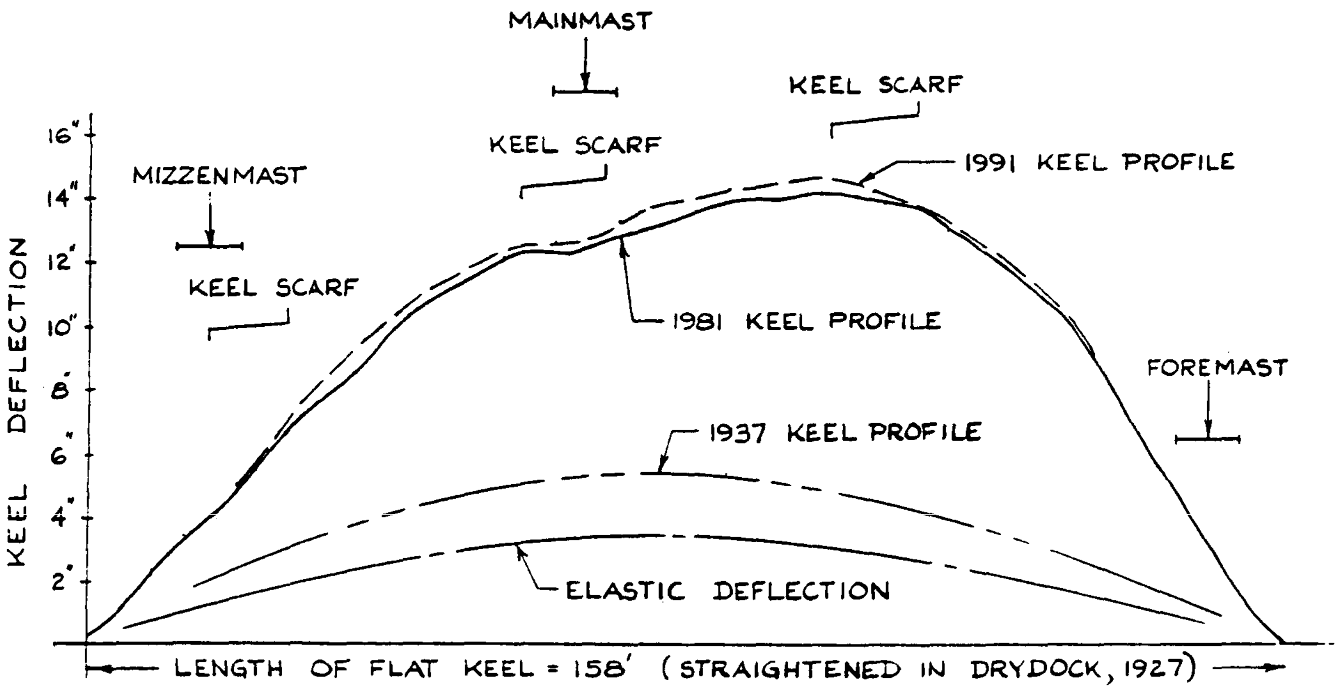

Figure 3. Recent keel deflection curves for USS *Constitution*.

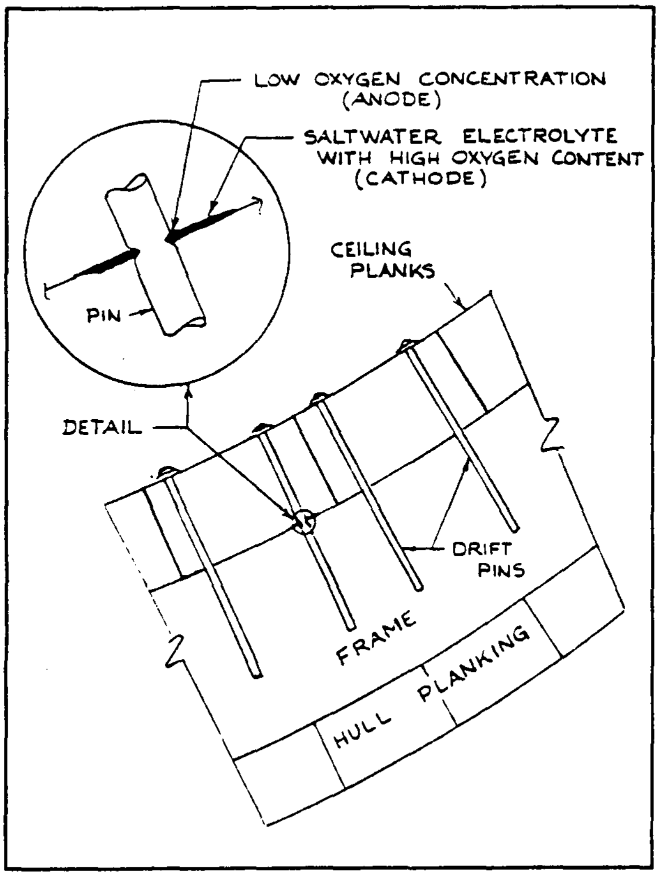

Figure 4. Crevice corrosion of a copper pin at the ceiling plank/frame interface.

strength that results from the removal and replacement of topside hull and deck planking, for example, can be offset by: (a) increased stresses on the keel and bottom hull planks (which are thought to be original), (b) increased longitudinal deflection in the hull, and (c) the fact that the new planking "builds-in" these increased stresses and deflections.

In the past, hull deformations and structural problems such as those just cited have been remedied by periodic overhauls and "restorations" in which hull form and structural integrity were restored to some degree by the large-scale replacement of materials. Today the underwater structure that is thought to be original comprises less than 10% of the total hull structure. As *Constitution* approaches her two hundredth birthday, it becomes increasingly apparent that approaches other than the maintain/overhaul philosophy which prevailed in the past are required to preserve what remains of the original ship. The following headings describe the most promising of current Navy efforts related to *Constitution's* preservation.

ULTRASONIC INSPECTION OF FASTENERS

The ultrasonic test apparatus (flaw detector) used to inspect *Constitution's* fasteners works on the same principle as sonar. The test equipment incorporates an oscilloscope which provides what is known as an "A-scan" presentation

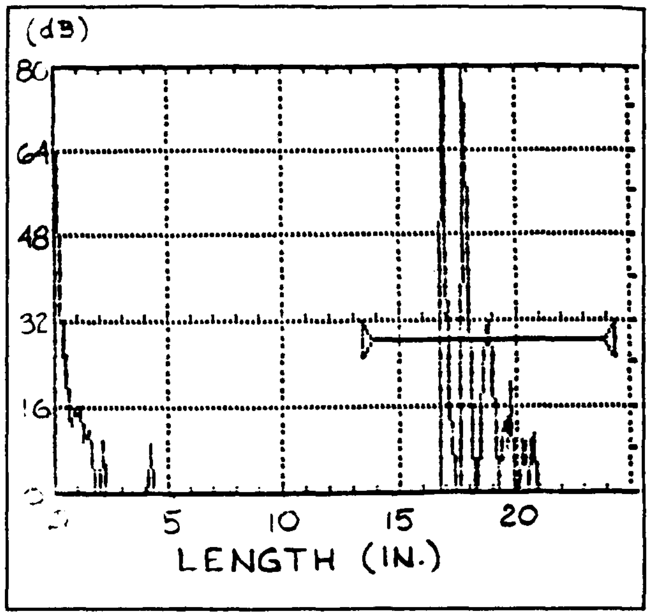

Figure 5. A-scan of 17-inch long copper alloy ceiling plank fastener (drift pin) from the starboard cable tier area. The pin is in sound condition with very little wastage.

and specially designed probes (transducers) that are able to focus sound waves through the length of a ship fastener. An ultrasonic pulse (sound wave) is transmitted by a selected transducer into the exposed end of a fastener. The pulse propogates through the fastener until it reaches a material of substantially different acoustic impedance from the fastener (i.e., wood or water). If the fastener is free of defects, the pulse will reflect, or "backwall," off the other end of the fastener back to the probe, where the flaw detector converts the time-of-travel for the pulse into a fastener length measurement. If the fastener is partially deteriorated, the flaw detector will display secondary signals along the length of the fastener, in addition to a backwall (length) measurement.

Fastener flaws such as fractures, deep pits, and body wastage will characteristically show up on the A-scan as either well defined peaks and spikes or sloping echos. Copper alloy fasteners often fail from the effects of various forms of corrosion, many of which take the form of leaching, whereby one element of the alloy is attacked and removed. Such a condition can be routinely identified by being able to recognize the distinctive attenuation, or scatter characteristic, in the A-scan.

Figures 5 through 8 show ultrasonic A-scan results for four copper pins which were located in the lower portion of *Constitution's* hull. Note from the figures that the pins in better condition (Figures 5 and 6) produce a strong backwall echo at the far end, and minimal signals from the near zone. while pins in poor condition (Figures 7 and 8) produce the opposite effects.

NONDESTRUCTIVE TESTING OF WOOD MEMBERS

Nondestructive testing (NDT) techniques for wood differ greatly from those for homogeneous, isotropic materials

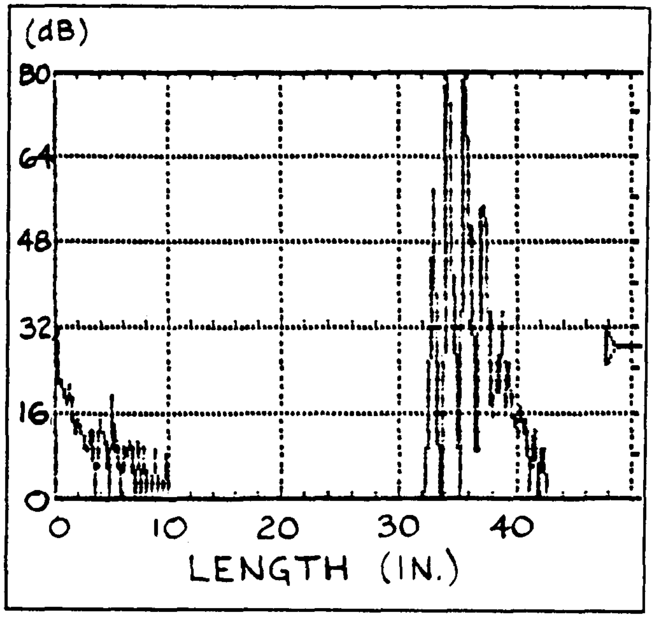

Figure 6. A-scan of 32-inch long copper alloy drift pin in the starboard sister keelson (sail locker area). The pin is in good condition with light wastage on the inboard 8-10 inches.

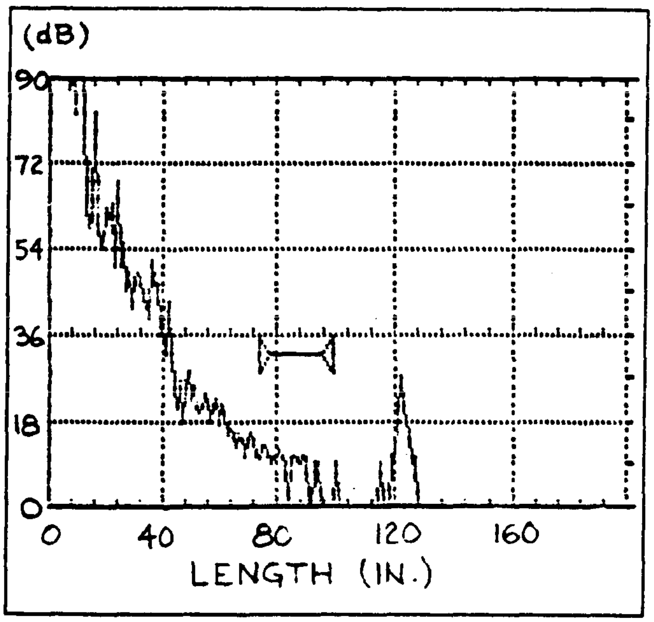

Figure 7. A-scan of 120-inch long copper alloy breasthook fastener in the lower stem area. The weak backwall and considerable attenuation indicate serious pin wastage.

such as metals. In those materials, mechanical properties are known and NDT techniques are used to measure thickness, or to detect the presence of irregularities, as was just described for fasteners. In wood however, irregularities occur both naturally and as a result of degradative agents such as bacteria or various fungi. Consequently, for wood, NDT techniques are used to help understand how natural and induced irregularities interact, so that meaningful strength assessments can be made. The following paragraphs describe

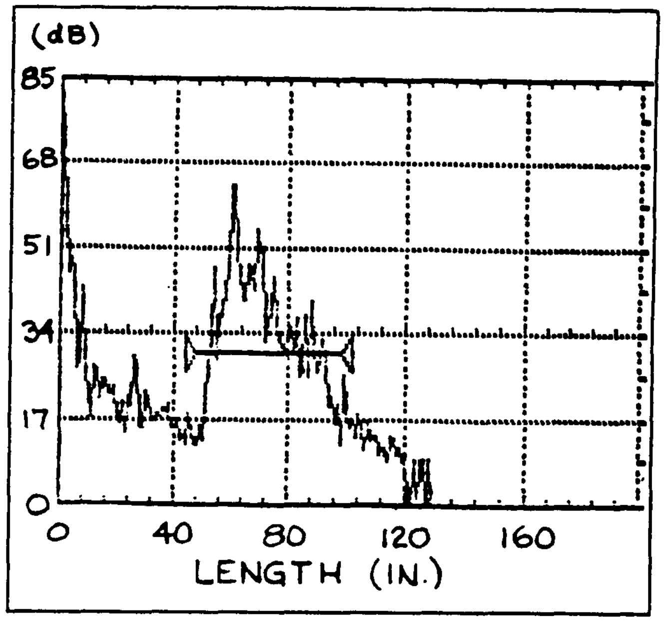

Figure 8. A-scan of lower breasthook centerline fastener in the oil locker. The absence of a backwall indicates that this fastener is defective.

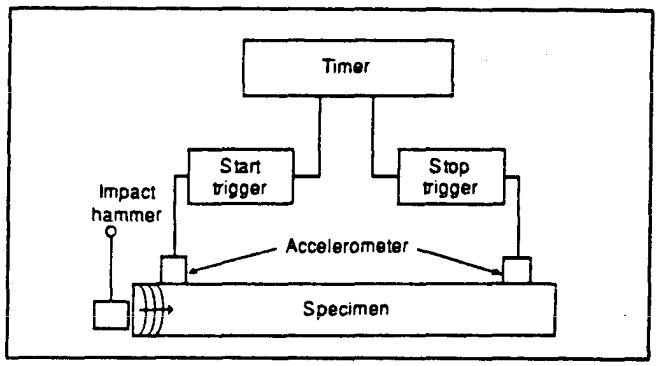

Figure 9. Technique used to measure impact-induced stress wave propogation in various wood products.

three NDT techniques which are being developed for use in combination, to evaluate *Constitution*'s wooden members.

Stress Wave Velocity Measurements

One promising NDT technique for macroscopic wood evaluation is to measure the velocity at which an induced stress wave travels through the wood. This technique has already been used successfully on a number of large structures to locate decay and estimate residual strength properties. The general basis upon which stress waves are used to evaluate the strength of a wooden member is that, for a given species, stress wave speed "C" is faster through sound wood than it is through wood that is weakened by decay. To determine "C," accelerometers are placed at two points on a member, and the distance between the two is measured (see Figure 9). A stress wave is then created by hammering on one side or one end of the member. The time it takes for the stress wave to travel between accelerometers is measured with a high speed timer, and stress wave velocity is computed simply by dividing the measured distance by this measured time.

On *Constitution,* the primary function of stress wave velocity measurements will be to locate areas of decay in large thick members. Since the pair of accelerometers can be nailed virtually any distance apart on the face of a beam or plank, velocity measurements in one area can be compared with velocity measurements in another, and decayed areas can eventually be isolated. Once a decayed area has been located, test borings and chemical analyses can be used to assess the extent of damage.

In addition to locating decay, stress wave velocity measurements can also be used in predicting the mechanical properties of a wooden member. For instance, once the stress wave velocity "C" has been calculated, the modulus of elasticity "E" of the member can be determined by:

$$E = C^2\rho$$

where is the mass density of the wood. For nondestructive in-place testing such as will be done on *Constitution,* the mass density is estimated based on actually weighing other wood specimens having the same species and moisture content as the piece being tested.

MICROSCOPIC INVESTIGATIONS

Microscopic analysis of a wood specimen can reveal a considerable amount of information that is not obtainable through other methods of nondestructive testing. Using a light and an electron microscope: 1) maximum stresses that have been applied to the wood can be qualitatively assessed through the absence or presence of cell wail buckling, 2) the presence of bacterial, fungal, or electrochemical degradation can be detected, and 3) peculiarities in the cell structure, such as the presence of reaction wood, can also be detected.

Since 1985, microscopic investigations of wood taken from *Constitution* have been conducted several times. On one occasion, wood shavings were removed from a ceiling plank in the hold which had cracked transversely, completely through the plank. What was unusual about this plank was that it had a tension break in an area that was presumed to be in compression. Microscopic analysis of the wood shavings revealed that the ceiling plank contained reaction wood (such as would come from a curved tree trunk), whose tendency to shrink longitudinally is far greater than in wood coming from a straight tree. It was consequently surmised that ventilation improvements which had been made in the hold since 1974 had caused the ceiling planks to shrink, and since this particular ceiling plank contained reaction wood, it shrank more than the surrounding planks and broke.

Another microscopic examination was made of chips and shavings taken from *Constitution's* starboard sister keelson and limber strake, to look for evidence of significant compressive stresses or creep. Results of the examination suggested very low compressive stresses and no wood creep effects away from fasteners.

Still another microscopic analysis was made on chips and shavings taken from lower portions of the ship's live oak frames. In general, the samples taken showed the frames to be lowly stressed and free of decay, but evidence was found of chemical degradation at copper pins (fasteners) and on the frame surfaces. Much of this degradation was attributed to the past practice of packing salt between frames to inhibit rot. Chemical analyses were subsequently made on these chips and shavings, for comparison with other live oak specimens which were mechanically tested.

CHEMICAL ANALYSES

At present, the principal benefit of performing chemical analyses on wood specimens is that such analyses often allow the causes of observed degradation to be better understood. These analyses are especially needed in the case of chemical degradation. However, research is also ongoing to establish relationships between the chemical composition and material properties of wood, so that material property information can be derived from a simple test bore, and used to complement stress wave velocity data.

From the chemical standpoint, wood has three major components: 1) cellulose, which is responsible for the strength of wood cells (fibers), 2) hemicellulose, which acts as a matrix for the cellulose, and 3) lignin, which serves as an adhesive that bonds fibers together. Additional to these are two minor components: 1) extractives, which contribute to wood characteristics such as color, taste and smell, and 2) ash-forming minerals such as calcium, potassium, phosphate and silica. For purposes of chemical analysis, cellulose and hemicellulose occur together as hollocellulose, and wood specimens are described as having four basic components: hollocellulose, lignin, extractives and ash. Figure 10 shows the relative amounts of these components that occurred in a number of live oak specimens, and Figure 11 shows a further breakdown of the hollocellulose components.

The specimens represented by Figures 10 and 11 formed a test series in which live oak specimens from *Constitution* materials were compared to live oak from other sources. All specimens were given both mechanical property and chemical tests to see if chemical analyses would produce indicators for mechanical strength. Unfortunately, as can be seen by comparing Figures 10 and 11 with Table 1, no correlation can be found between mechanical properties and the presence of a particular wood component. Further chemical tests for "% acetyl," alkali solubility, and degree of polymerization on the wood test specimens also failed to produce a correlation.

A particularly interesting result which emerged from this series concerned the "PO" test specimens (see Note 5 of Table 1 for description) which were completely lacking in structural integrity due to separation along annual growth rings. The deterioration of these specimens, which occurred while they were stored underwater at Portsmouth, NH, was so extensive that l-inch × l-inch × 16-inch pieces for mechanical testing could not be obtained from the large timbers that were available. However, as Figures 10 and 11 show, the chemical composition of "PO'" wood shavings, including "% lignin" was similar in all respects to the chemical com-

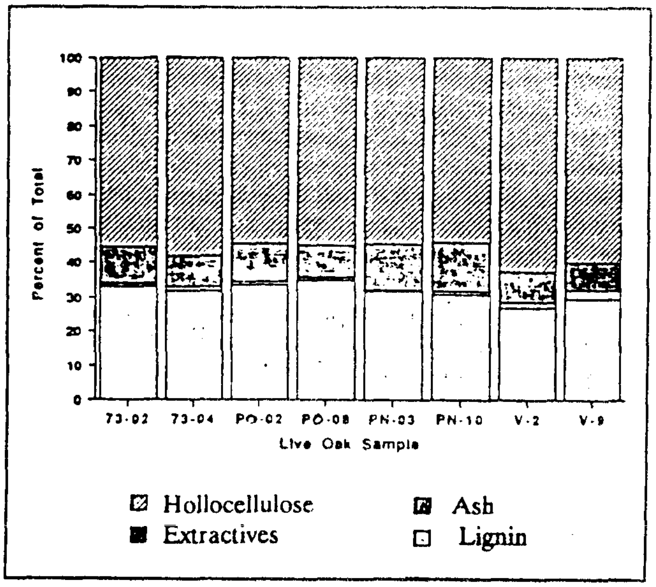

Figure 10. Chemical analysis of eight live oak specimens showing the four basic components of wood.

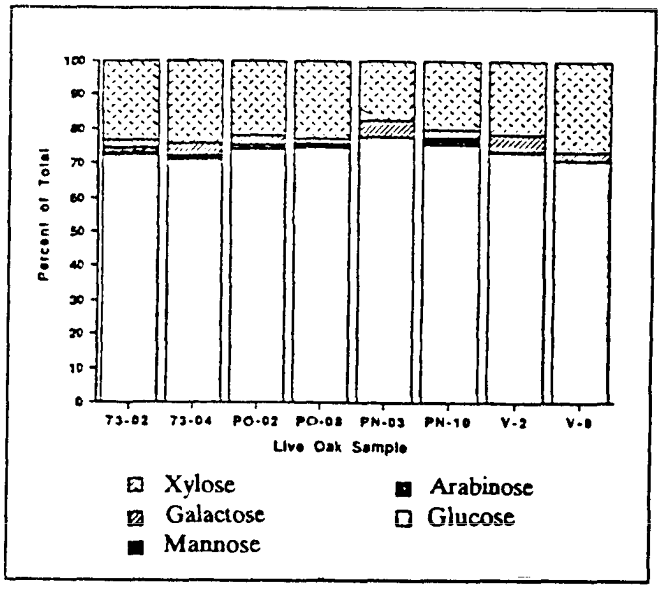

Figure 11. Ash-free analysis of holocellulose.

Table 1.
Mechanical Properties from Live Oak Tests

Live Oak Test Specimen	Modulus of Rupture (psi)	Modulus of Elasticity (psi)	Compression Perp. to Grain (psi)	Compression Parallel to Grain (psi)
73-02	9,200	1,800,000	1,900	6,300
73-04	8,700	1,550,000	1,900	6,100
PN-03	—	—	—	4,300
PN-10	9,300	1,610,000	600	4,400
V-2	9,300	1,030,000	—	4,100
V-9	—	—	—	4,000

Notes:
(1) 73-" " materials were removed from the *Constitution* in 1973 and stored in the USS *Constitution* Museum .
(2) PN-" " materials had been buried since 1855 in Pensacola, FL .
(3) V-" " materials were newly cut .
(4) All properties have been adjusted to a 25% moisture content.
(5) PO- " " materials shown in Figures 10 and 11 had been buried in Pensacola, FL from 1855 - 1926, and in Portsmouth, NH from 1931 - 1986. These materials had extensive ring separation, and suitable specimens for mechanical testing could not be obtained.

positions that were found on sound wood test specimens. At this point we can therefore only conclude that chemical analyses provide information which can be useful in interpreting other data, but do not provide data that is useful by itself.

COMPUTER MODELING

INITIAL MODEL

Modeling *Constitution's* hull on a computer using the finite element method (FEM) was begun in 1986. The initial purpose of the modeling was to see if diagonal metal strapping on the hull could effectively be used to stiffen the ship against hogging. Two historical findings which caused interest in the strapping were that: 1) the British, in the 1820s, added diagonal steel strapping to the inside of a ship which had a hull similar to that of *Constitution,* and 2) the HMS *Unicorn,* another ship built by the British with diagonal strapping in the 1820s, was still afloat and had less than 2-inches of longitudinal hull deflection. Neither of these findings provided clear evidence as to the effectiveness of diagonal strapping, however, since the ship similar to *Constitution* no longer existed, and the HMS *Unicorn* had spent her entire life in a laid up condition, tied to a pier.

Whereas *Constitution* is a three-dimensional, curved surface structure having thousands of fasteners and structural members of varying properties, it was clear at the outset that a number of approximations and simplifying assumptions had to be made relative to the ship's structural configuration and material properties. The most important of these was the assumption that the effectiveness which various hull stiffening schemes had on overall hull deflection could be modeled using combinations of truss, beam and isotropic plate elements. *Constitution's* side and bottom, for instance, were modeled using a combination of isotropic plate elements and beam elements at the forward and aft edges of these plate elements, to reflect the ship's greater stiffness in the transverse direction. Using this approach, half of the ship was modeled with 671 nodes and approximately the same number of elements. Figures 12 and 13 show the model from the outside and inside respectively (with hidden lines suppressed).

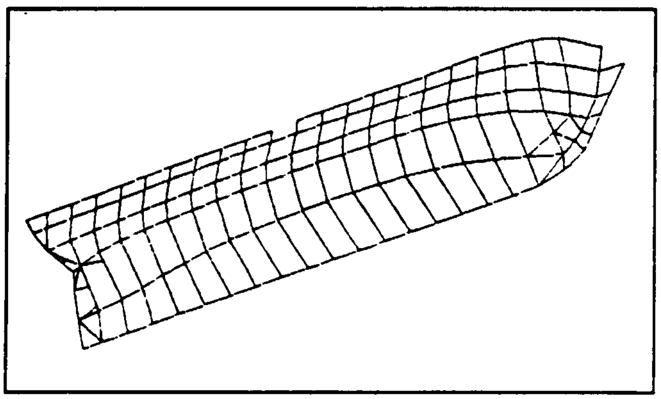

Figure 12. Hull gridwork on the initial FEM model (hidden lines suppressed).

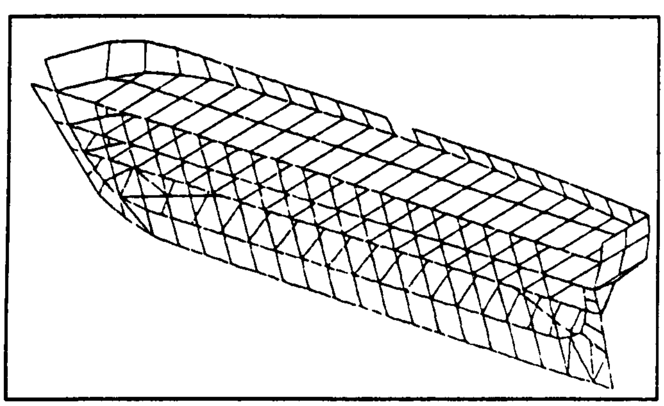

Figure 13. Initial FEM model geometry as seen from centerline, looking outboard (hidden lines suppressed).

In order to establish "equivalent" material properties that characterized the actual ship, trial-and-error adjustments were made to elemental material property data until the behavior of the computer model mimicked that of the ship. The main data point used to define the ship's longitudinal flexibility was taken in 1981, when 31,000 pounds of cannon were removed from the ends of *Constitution* and 40,000 pounds of lead ballast were added just forward of midships, causing a l/4-inch deflection. (In actuality, since the ship's total longitudinal deflection was about 14 inches at that time, the 1/4-inch measurement amounted to a temporary reduction to 13-3/4 inches.) To recreate this data point, the isotropic plate elements making up the hull of the computer model were assigned an "equivalent" elastic modulus (E) of only 80,000 psi. This modulus accounted for deflections due to both bending and shear. With Poisson's ratio set at μ = .50, the corresponding shear modulus (G) was about 26,700 psi. By comparison, the beam elements which represented the ship's transverse framing (i.e. the beams at the forward and aft edges of the shell plate elements) provided an "equivalent" elastic modulus for the double sawn frames of about 550,000 psi.

The difference between the equivalent elastic moduli found for the longitudinal planking and transverse frames is primarily the result of differences in the way they resist applied loads, rather than differences in material properties. When loaded longitudinally, Constitution's planking provides slipping planes, leading to greatly reduced shear resistance under in-plane loads. Consequently, the plate elements had to have a low shear modulus, and because they were isotropic, also had to have a low equivalent elastic modulus to account for shear deflections. On the other hand, *Constitution's* double sawn transverse frames have staggered joints and are loaded laterully as beams, so their equivalent elastic modulus is 30%-40% of the elastic modulus that would be expected if the double sawn frames were made from two continuous futtocks.

A footnote to this discussion on the initial computer modeling of *Constititition* is that a limited amount of diagonal strapping at the turn of the bilge, such as the British put on their 1820 era ships, was found to have little effect on *Constitution's* hull stiffness. Extensive double diagonal strapping from the keel to the cap rail, such as was done on

World War I era wooden ships, would be required to make any appreciable difference in the ship's shear stiffness.

REVISED MODEL

Recognizing the limitations of the initial FEM computer model, revisions on the model were started in 1989. The first major step taken to improve the computer model was to change from a main-frame run FEM program and data base to one that could be run completely on a personal computer. This changeover was made possible by the great advances that were made in personal computers during the 1986-1989 time frame, and drastically reduced the costs of FEM modeling. With the transition to a personal computer completed, the next steps were to change the *Constitution* FEM model as follows:

1) The half-model nodal coordinates were mirrored to make a full model. This alleviated several problems associated with assigning degrees-of-freedom to centerline nodes, although it doubled the size of the model.
2) The method of support for the model was changed from using a single fixed point or two pinned joints to using a system of springs or "boundary elements." This reduced the potential for getting unrealistic local deformations from differences in applied loads around a point of support.
3) The beam/isotropic plate element combinations that had been used to get different directional properties were completely discontinued in favor of using orthotropic plate/shell elements.

From the standpoint of technical accuracy, this last step of converting to orthotropic plate/shell elements was the most important, and certainly the most involved.

In order to estimate properties for the plate/shell elements which represented *Constitution's* hull planking, transverse framing and ceiling planks combined, a number of 1/16 scale model beams were constructed, and tested in bending and shear. As Figure 14 shows, the test pieces were made using white oak for the outside planks, live oak for the frames and Douglas fir for the ceiling planks, just as on the ship. Fastening on the test pieces was accomplished completely by wire brads, set to the same pattern as the copper pins used on the ship.

The shear and bending tests which were subsequently conducted with these pieces yielded two important results. First, shear tests (see Figure 15 for test method) showed that the longitudinal shear modulus which resulted from slippage between model planks was only about 3,500 psi. Secondly, bending tests made on specimens having a Length/Depth = 8.4 revealed that the model beams had a much greater "equivalent" elastic modulus in bending than the 80,000 psi "equivalent" modulus that had been calculated for *Constitution* earlier. The implications of this result are that shear effects on the ship are even greater than they were on the model beams, and the longitudinal shear modulus (G) for *Constitution's* hull is less than the 3,500 psi that was determined for the model test pieces.

Returning to the FEM computer model, a longitudinal shear modulus of 2,500 psi was assumed for use on the orthotropic plate/shell elements of the hull. Longitudinal elastic moduli inputs for plate/shell elements were based on published and measured values for solid white oak (E_L = 1,800,000 psi), Douglas fir (E_L = 1,600,000 psi), and live oak (E_L = 1,900,000 psi). The only adjustments made to these values were for moisture content (E_L for watersoaked oak is about 30% less than E_L for dry oak), and the presence of butt joints within elements in tension (an element representing 10 plank widths and 2 butt joints would have a 20% reduction in EL under tensile stress). Using this approach to elemental material property development, the revised FEM

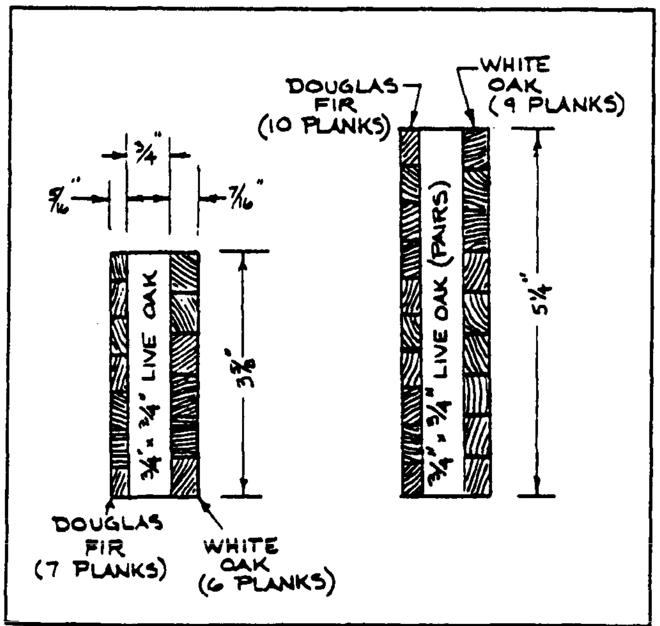

Figure 14. Cross-sections of 1/16 scale wooden models (test specimens) of *Constitution's* sides.

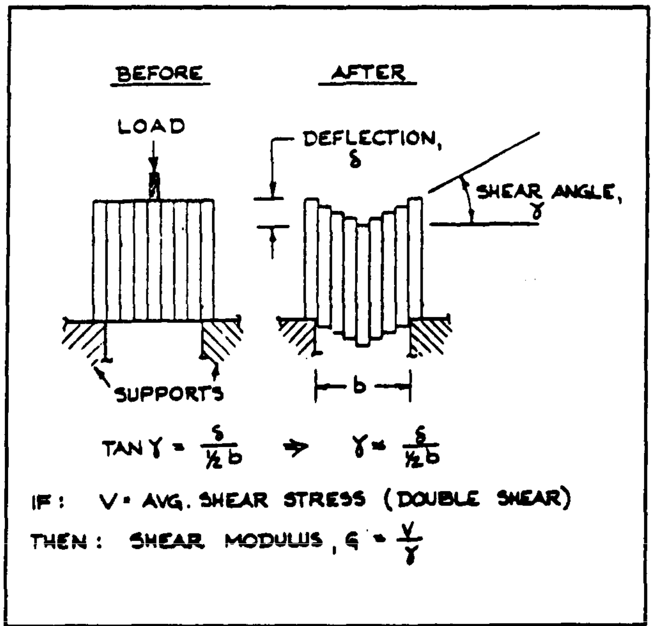

Figure 15. Method used to determine shear modulus for 1/16 scale model test specimens.

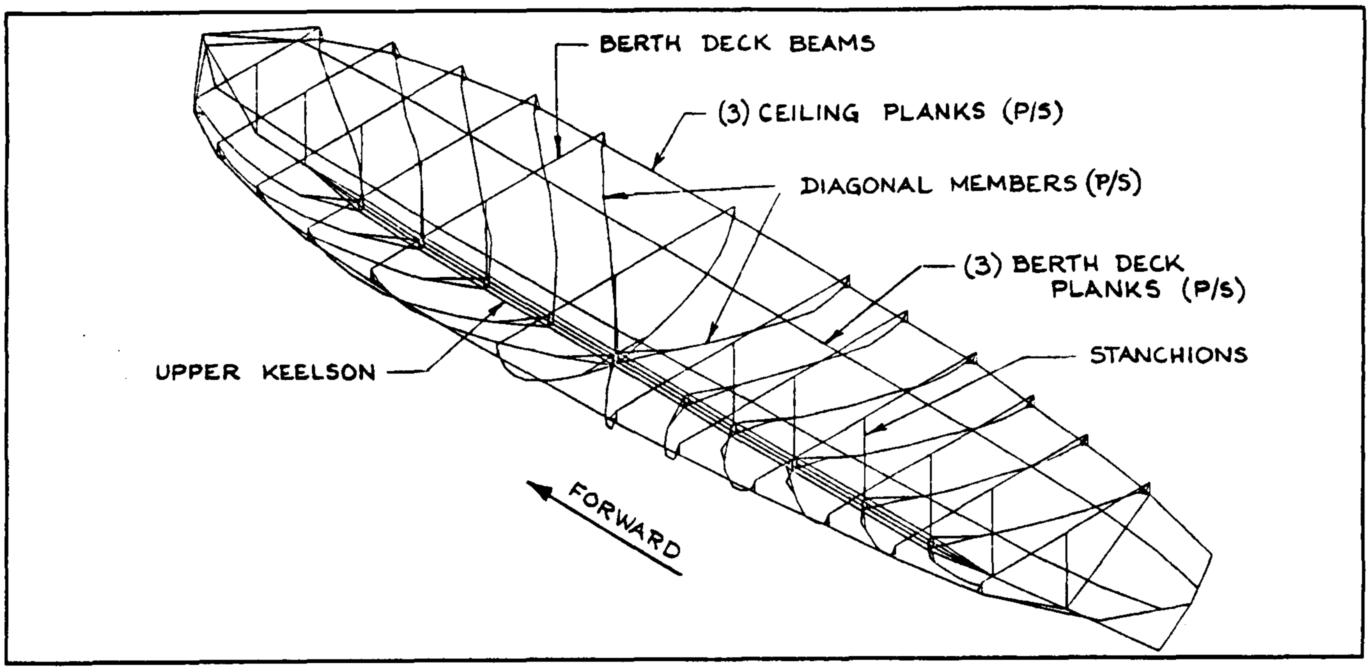

Figure 16. FEM representation of the internal supporting framework designed for *Constitution*.

model was ultimately found to correlate very well, in terms of longitudinal flexibility, with the initial model and the single data point that had been measured on the ship.

CURRENT COMPUTER MODELING EFFORTS

In the process of developing a finite element model for *Constitution,* a great deal was learned about the ship's structural behavior. Current computer modeling efforts are directed at applying this knowledge towards preserving the ship in an afloat condition. Over the past decade, several schemes have been considered for stiffening and strengthening the ship, and several other schemes have been considered for reducing hull loads by providing additional buoyancy beneath the ends of the ship. In December 1990, design work was begun on an internal framework to help support *Constitution* while she remains afloat. FEM modeling has been used extensively in the design of that framework.

Figure 16 shows the FEM computer model representation of the supporting framework by itself. The construction of the framework and the manner in which it would be incorporated into the hull are the next topic of discussion. The interaction between the framework and *Constitution's* hull are being investigated with yet another, more detailed, FEM model.

INVESTIGATIONS ON FIBER REINFORCED COMPOSITES

After considering a number of materials for use in the construction of the framework, fiber reinforced composites were selected as being the best choice. The advantages of using fiber reinforced composite materials in this particular application are:

1) Composites do not require any welding or "hot work" in fabrication.
2) Composites are far stronger than wood, and their strength and stiffness properties can be adjusted using different types and orientations of fibers.
3) Composites are more formable than metals, and can be designed to avoid the possibility of galvanic corrosion with existing copper fastenings on the ship.

While the usage of composites aboard *Constitution* has the potential for stirring up feelings of ambivalence because of the "modernness" of composites, one must also consider that, in 1797 or 1812, the ship did not have electric lighting, a fire alarm system, a sprinkler system, or a ventilation system. These all exist on the ship today because they help to ensure the ship's safety and continued preservation. The rationale and justification for using composites in a supporting framework are similar.

The framework represented by Figure 16 could be incorporated into the ship as shown in Figure 17. For clarity, Figure 17 shows only those members below the berth deck which would be of composite. Darkened members are on centerline, and outlined members are at the ship's side. The wooden structural members which would be displaced by composite counterparts have all been installed since 1926, and consequently have no historical significance. Specifically, the supporting framework installation would require that the following wooden members be replaced with composite:

- (12) berth deck beams
- (6) berth deck strakes (3P/3S)
- (12) pairs diagonal knees
- (12) orlop deck stanchions

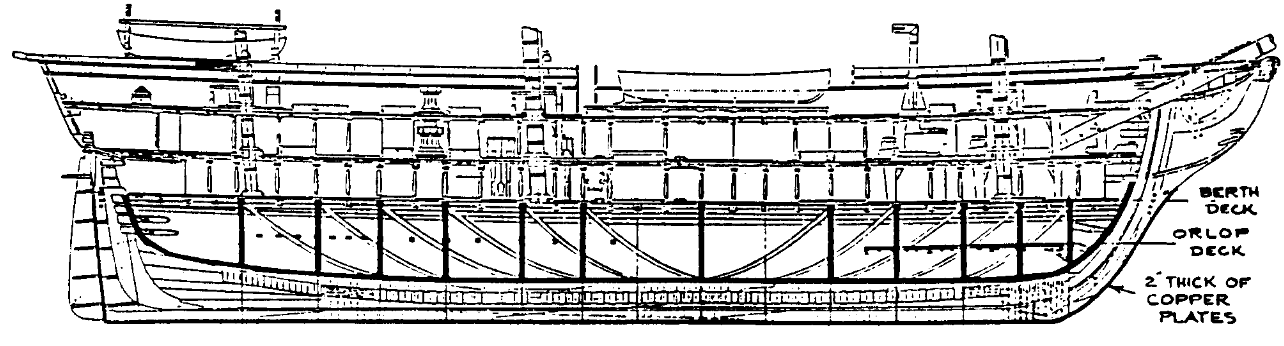

Figure 17. Inboard profile of *Constitution* showing how the composite framework would be incorporated into the hull structure and provide support to the ship.

- (6) orlop deck ceiling plank strakes (3P/3S)
- (1) upper keelson assembly (including stem and sternpost pieces)
- (1) forward breasthook (1) aft breasthook

To complete the framework, the following components would need to be added inside the ship's hull, against the ceiling planks:

- (1) 9" x 16" transverse frame assembly
- (11) 9" x 16" pairs of diagonals, with bottom connection assemblies

All composite members would be either smoothed and painted, or covered with wood to make the composite indistinguishable from surrounding wood members. Based on building specifications which exist for a 44-gun frigate in the early 1800s, it is believed that *Constitution* originally had six pairs of 9-inch × 16-inch live oak diagonal "riders" inside the hull, although these riders do not exist in the ship today. Consequently, the use of diagonal riders has historical precedent, though the live oak diagonals used originally would have been far less effective than the composite diagonals in the supporting framework.

Using copper plates on the outside of the ship to distribute fastener loads, the ship would be through-bolted to the composite framework at the stem, sternpost, and along the keel. In addition to holding the ends of the ship to the composite framework, the copper plates would "sandwich'" scarf joints in the keel and lower keelson against the composite upper keelson, thereby eliminating secondary deflections in those areas.

The composite material properties which are required to construct the supporting framework just described are listed in Table 2, These properties represent a composite which is about three times as strong and stiff as the glass reinforced plastic (GRP) that is typically used in boat construction, but

Table 2. Mechanical Properties for USS *Constitution* Supporting Framework Composite Materials.

	Lengthwise	Crosswise
Tensile stress	100 ksi	30 ksi
Flexural stress	120 ksi	35 ksi
Compressive stress	70 ksi	35 ksi
Tensile modulus	5.0 Msi	2.2 Msi
Flexural modulus	5.4 Msi	2.2 Msi
Compressive modulus	4.5 Msi	1.7 Msi

which is not as high strength as the composites used in aircraft. Experience to date has demonstrated that these properties can be met using very high density E-glass or S-glass reinforcing fibers in an epoxy or vinylester matrix. From the cost standpoint, the best cost combination is to use the high density E-glass fibers in a vinylester matrix.

To fabricate the large members required for *Constitution,* 1/8 to l-inch thick composite planks of various widths would be laminated together, just as if they were wooden planks going into a "glulam" or built-up wooden laminate. An epoxy adhesive would then be used to bond planks together, and to bond built-up members together. To provide clamping action during fabrication, as well as redundancy in bonded joints, bolts would also be used for mechanical fastening.

Thus far, two 1/16 scale composite models of the support framework just described have been fabricated and tested, with promising results. The first model was tested inside a wooden structural model of *Constitution,* as shown in Figure 18. The purpose of this model test was to verify that a composite framework, with curved diagonals, could be made to favorably interact with a relatively weak and flexi-

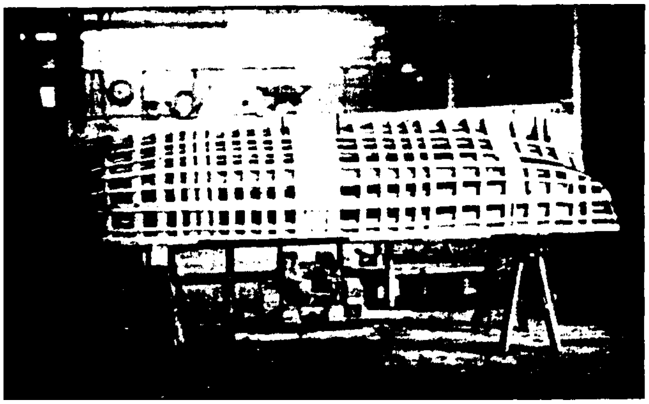

Figure 18. Testing of first 1/16 scale model composite framework inside 1/16 scale wooden structural model of *Constitution*.

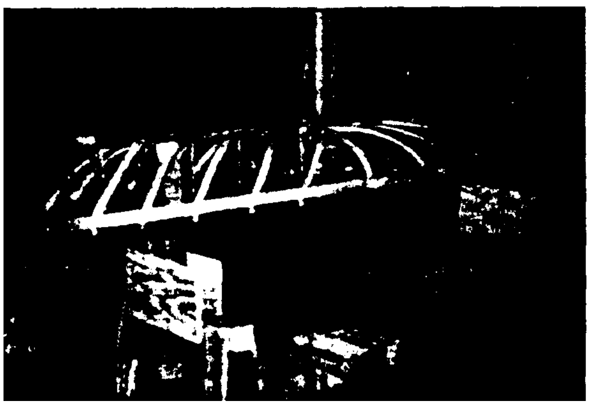

Figure 19. Second 1/16 scale model composite framework, shown during initial test.

ble wooden structure surrounding it. The test setup for the first composite framework/ wooden model combination was very simple: 1) the model was inverted and supported at the ship's maximim shear points, 2) a loading tray was hung from the keel to provide maximum bending where it occurs on the ship, and 3) weights were added to the tray until the ship's full bending moment was attained (scaled by $^{1}/_{256}$). Results of this test suggested that, under 100% of the ship's present stillwater loading, the composite framework alone would deflect four to five inches at full scale. As was shown in Figure 3, this amount of flexibility (elastic deflection) is similar to that of *Constitution*, indicating compatibility in that regard.

The second model was constructed to verify computer predictions for stress levels and deflections in the supporting framework alone, under various loading conditions. Unlike the first model, which was constructed from conceptual sketches, the second model was developed in conjunction with detailed design drawings for the full-size framework. As such, the geometry, construction methods, and joint designs used on the second model are generally representative of what would be used on the full-size framework for *Constitution.* The model is shown in Figure 19 in its initial test setup, which is similar to what had been used previously for the composite framework/wooden model combination.

Without a surrounding wooden framework to distribute loads into the composite, the composite framework alone behaved quite differently than the composite framework/wooden model had in the first tests. The composite framework alone did, however, provide test data which allowed the computer model for it to be validated.

CONCLUSION

Modern technology is now playing a role in the preservation of important artifacts, buildings, historic sites, and other wooden ships throughout the world. The need for today's technology in preservation stems from a desire to keep physical objects from the past for time periods that extend far beyond what the creators of those objects probably ever conceived of. In view of the fact that *Constitution* currently retains only a very small percentage of her original material, it becomes clear that the ship is destined to become a complete replica if past practices of removing and replacing material continue to be the sole method by which the ship's existence is perpetuated. Only through the added application of today's technology can this course of events be altered.

Considering the number of other historic vessels in the world that have been placed under cover or in a dry berth, one wonders how much longer *Constitution's* special status as the "oldest commissioned ship afloat in the world" can be made to last. The topics which have been discussed in this paper (i.e., non-destructive test methods for fasteners and wood, computer modeling, and investigations on a composite supporting framework for the ship) are all directed at retaining this special status for *Constitution,* besides contributing to her preservation. It is hoped that, in presenting these topics, this paper has helped to stimulate both awareness and interest in the ship's preservation.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge contributions made by personnel from the USS *Constitution* Maintenance and Repair Facility, and Forest Products Laboratory (FPL) who helped make this paper possible. Particular acknowledgements are made to Jerry Winandy, Roger Rowell, Terry Highley and Charles Gerhards of FPL.

BIBLIOGRAPHY

1. Ross, R.J. and Pellerin, R.F. "Nondestructive Testing for Assessing Wood Members in Structures: a Review," Forest Products Laboratory Report FPL-GTR-70, August 1991.
2. Witherell, P.W. , "A Study of Wooden Ship Hogging—the USS CONSTITUTION," *Ancient Interface XVI Symposium*, AIAA/SNAME, October 1986.
3. Winandy, J.E., "Evaluation of Live Oak Submerged Underwater for 50 years and Proposed for Use in the USS *Constitution*," *Forest Products Journal*, Vol. 34, No. 5, May 1984.

Printed on Recycled Paper