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Strength Properties of Drydocking Timbers and Blocks

VIIIB-2

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ABSTRACT

Knowledge of the strength characteristics of docking block timbers is a key element in safely drydocking ships. such knowledge has become especially important for the Navy, because of changes in Navy ship design, coupled with heightened safety concerns regarding seismic loading. Although, over the years, timber strength knowledge has evolved to a general level, it has never reached the detailed level required to meet today's needs. This paper describes a study to gain timber strength knowledge at the detailed level by testing actual docking block timbers. The tests were conducted on individual timbers, timbers formed into layers, and timbers within full-sized docking block build-ups.

LIST OF ACRONYMS

DTRC	David Taylor Research Center
FSPL	Fiber Stress At Proportional Limit
LVDT	Linear Variable Differential Transformer
MIL-STD	Military Standard
MOE	Modulus of Elasticity
NAVSEA	Naval Sea Systems Command

INTRODUCTION

For most of the history of drydocking ships had short bow and stern overhangs, wide keels, and relatively uniform longitudinal weight distributions. When drydocked, these ships were supported by a number of low, timber, docking blocks that ran the length of the keel (1,2). Each block bore approximately the same, relatively modest load. More recently, and especially following the Second World War, ships have changed. Today's ships, in particular the combatants, typically have long bow and stern overhangs, narrow keels and areas of high weight concentration. In addition, they may have sonar domes that extend below the keel. These changes have impacted docking blocks. The long bow and stern overhangs increase the loading at the blocks closest to the overhangs; the narrow keels increase local loads on docking block soft caps: the high weight concentrations increase loading on particular blocks; and the sonar domes that extend below the keel can require high, potentially unstable, build-ups of docking blocks. Coupled with these changes are safety concerns with seismic loading (3).

In recognition of these matters, in the late 1980s the Naval Sea Systems Command (NAVSEA) contracted Associated Forest Products- Consultants, Inc., to conduct a study to provide definitive data on the compressive strengths of timbers that are used in docking blocks for U.S. Navy dry docks. The study comprised testing actual docking block timbers in the University of Washington Structural Research Laboratory and analyzing the results of those tests. This paper describes the study and its procedures, results, conclusions and implications.

NAVY DOCKING BLOCKS

All Navy drydocking facilities employ docking blocks as the means of supporting ships in dry dock (2). Each Navy shipyard typically has over 1,000 blocks and certain Navy shipyards have over 3,000 blocks in service. Figures 1-3 provide examples of Navy docking blocks. Figure 1 illustrates an all wood keel block; Figure 2 shows a concrete and wood composite block build-up (the Navy Standard Composite Block); and Figure 3 illustrates a sand block. All of these blocks include timber in their construction, and in all cases the timber is loaded perpendicular to the grain. Oak and Douglas fir are the wood types that are most commonly used in these docking blocks.

PREVIOUS STUDIES

Wood, when used for structural purposes, is almost always stressed parallel to the grain. Docking block timbers are a notable exception: they are loaded and stressed perpendicular to the grain. Figure 4 illustrates these two

loading orientations. As might be expected, relatively little is mentioned in the literature about wood which is loaded perpendicular to the grain. However, some studies have been published that address perpendicular loading in general and keel block loading in particular. The following paragraphs describe examples of these studies.
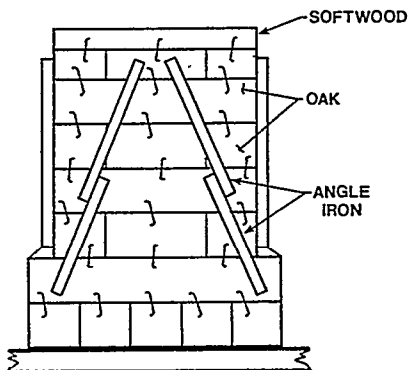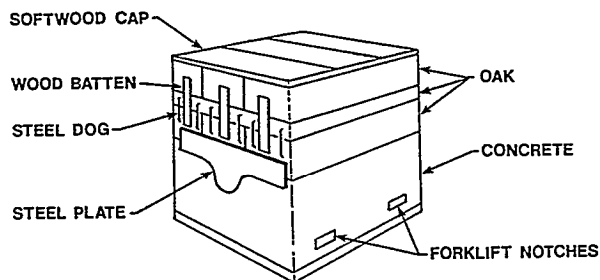

Figure 1
All Wood Keel Block

Figure 2
Composite Block Build-Up

Two landmark studies were conducted as a result of the failure of the docking blocks under the USS South Carolina on May 29, 1924 at the Philadelphia Navy Yard (4). To determine the cause of the failure, compressive tests on docking blocks were carried out at the U.S. Department of Agriculture Forest Products Laboratory and the Washington Navy Yard. The blocks were comprised of oak timbers, each measuring 35.6 x 35.6 x 121.9 cm (14 x 14 x 48 inches). The tests examined the compressive strength of the timbers and considered variables such as high block instability, moisture content, duration of loading and timber defects. Full size timbers and model blocks 3.2-5.1 cm (1.25 to 2 inches) square were tested. Selected results of the tests

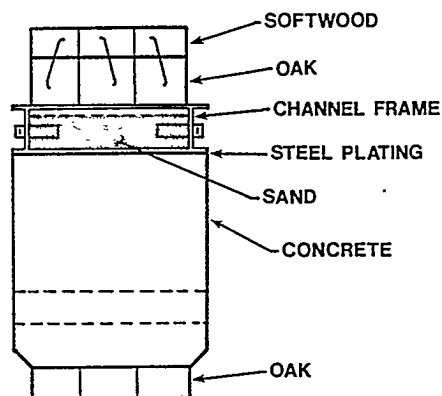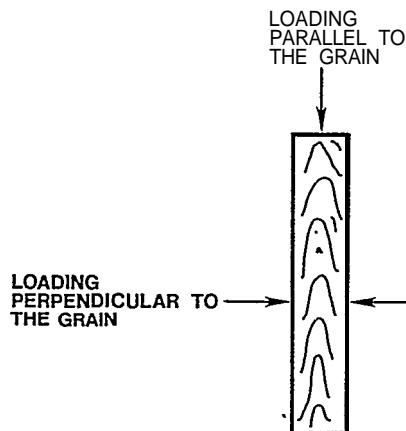are presented later in this paper.

Figure 3
Sand Block

Figure 4
Wood Loading Orientations

Other studies have developed standard tests for wood strength. In the standard transverse compression test for wood, the load is applied through a 5.1 cm (2 inch) wide steel plate across a 5.1 x 5.1 cm (2 x 2 inch) clear wood specimen 15.2 cm (6 inches) long. Test results are used to develop recommended bearing stresses for joists, beams, and stringers loaded perpendicular to the grain. Data published in the Wood Handbook (5) for all commercial species are based on this test, described in ASTM D-143-52 (6). Other studies have used the same 5.1 cm (2 inch) bearing plate, or only a somewhat wider one (13.3 cm, 5.25 inches) to determine compression strength perpendicular to the grain values for Douglas fir and other structural species (7). Because these compressive tests were performed with a bearing plate, the modulus of elasticity (MOE) cannot be

determined. Nor are MOE values in compression perpendicular to the grain available elsewhere in the literature.

There is a limited record of earlier efforts to deal with keel block properties and problems. The "History of the Development of the MIL-STD for Drydock Blocking Systems" (8) mentions that a major gap in the proposed MIL-STD is lack of data on large timbers. Also from the same reference, comments on the draft of NAVSEA's Proposed Drydock Blocking Systems MIL-STD by various shipyards reveal an inconsistent understanding of allowable stresses on keel blocks.

Tarr (9) tested small samples of Douglas fir, white pine, and white oak to failure under compression perpendicular to the grain in full bearing and concluded that the fiber stress at proportional limit (FSPL) for the softwoods was about 1,720 kPa (250 psi) and for the white oak was about 4,140 kPa (600 psi) (the fiber stress at proportional limit, or FSPL, is where the load-deflection curve departs from a straight line).

Naval Ships Technical Manual, Chapter 997 (10) cites the load-deflection curve for a "typical composite block" which indicates a FSPL of about 3,450 kPa (500 psi). This reference also lists deflection data for tests on eight composite keel block buildups (these tests will be discussed later in comparison with results of the present study).

Bath Iron Works instrumented two keel blocks to determine block loads during drydocking (11, 12, 13). The instrumented blocks measured vertical loads under two ships, the USS Scott (DD-995) and the USS Conolly (DD-979). Load cells were inserted in one keel block for each ship, replacing a 15.2 cm (6 inch) layer of oak in an oak and concrete composite block. Each load cell was comprised of four low profile 152 tonne (150 ton) capacity hydraulic jacks placed between two steel plates. The DD-995 load cell had a 1.22 meter (4 foot) length along the keel, while the DD-979 load cell had a 1.83 meter (6 foot) length along the keel. The load cell measurements helped to validate a drydock block loading computer program.

Crandall (14) tested one red oak and four softwood timber specimens and determined FSPL and MOE for each specimen. The FSPL ranged from 1,520 kPa (220 psi) for white pine to 3,450 kPa (500 psi) for Douglas-fir and was 4,830 kPa (700 psi) for red oak. "Wet" specimens in these tests produced the same results as "dry" which probably reflects an inadequate period of water immersion before testing. Crandall's work additionally showed that continued loading above the FSPL produced a "compressive range" where small increases in loads resulted in dramatic increases in deflection (indicating an extremely

low MOE); and if loading continued, a point was reached where load increased rapidly again for a small increase *in* deflection.

Palermo's investigation of pressures on keel blocks during the drydocking of three aircraft carriers (15) described the use of specially designed load cells consisting of fluid-filled "metalwafers" in selected keel blocks to record actual block loads in comparison to theoretical projections. Palermo showed that the maximum recorded block pressures were at least twice as great as the nominal pressures (total weight divided by block area). The maximum load recorded on one block was 3,590 kPa (521 psi), but the first readings of the pressure wafers were two hours after docking. In two out of three cases the highest load recorded during the docking was borne by the foremost block of the stern blocks. He observed that the sternmost blocks deflected a great deal as they were first loaded during docking and never did fully carry their share of the load thereafter.

Collectively, these studies indicate a general understanding of the approximate average level of FSPL of the common drydocking timbers, and show that docking loads probably have not, in the past, generally exceeded these levels. However, with the possible exception of the two studies cited in (4), it is clear there is no previously available comprehensive data on compressive timber strength that can be drawn on to develop docking plans that involve more difficult drydocking situations such as long overhangs and sonar domes, or for accurately predicting the compression of the the blocks when loaded.

MATERIALS AND METHODS

Returning to the present study, the following paragraphs discuss the types of wood tested and the testing methods. Two types of wood were tested, oak and Douglas fir. Both of these woods are typically used in Navy docking blocks. As shown in Figure 2, oak is used for the body of the block and Douglas fir is used for the soft cap at the top of the block.

The test timbers were selected from several Navy dry docks to provide samples typical of the wood species, sizes, and ages. At shipyards, timbers are usually stored outdoors. Likewise, they were stored outdoors at the test site until being moved to the laboratory for testing. A data sheet was prepared for each timber to record information such as an identification code number, dimensions and weight. A grid of 2.5 cm (1 inch) squares was drawn on one end of each timber to aid in examining distortion during and after loading. Finally a reference photo was taken of the gridded end surface and also of the loaded surface to illustrate knots, checks, splits and other characteristics, if any.

The moisture content of timber can

greatly affect its strength properties. Therefore, shortly before testing, a 2.5 cm (1 inch) diameter core was drilled vertically through each timber in the central area of the face to be loaded. The core was wrapped in plastic film and later was cut into 2.5 cm (1 inch) long sections. The moisture content of each section was determined by the oven-dry method. The moisture content data on the sections indicated the gradient within the timber and the average of the sections was used for moisture content. Specific gravity was also determined on two sections from each core as a measure of timber density.

Compression tests were performed on three timber arrangements: individual timbers: groups of timbers arranged in a single layer or in three layers: and on composite block build-ups consisting of several layers of timbers on top of a concrete block. The general compression test procedure was the same for all three arrangements. The following paragraph describes the general procedure. Succeeding paragraphs describe variations for each timber arrangement.

Each timber (or set of timbers) was tested in compression using a 10.7 million Newton (2.4 million pound) compression capacity Baldwin Test Machine. The timber to be tested was centered under the head plate of the test machine such that the load was applied to the wide face perpendicular to the grain, similar to normal drydock loading conditions. Vertical and horizontal linear measurement scales were arranged next to the gridded end of the specimen for visual reference and the machine head was lowered to contact the timber. Then the timber was loaded in compression. Measurements of timber deflection during loading were obtained by two linear variable differetial transformers (LVDTs) placed under the loading head of the test machine at two opposite corners of the test timber. At the conclusion of the test, the timbers were returned to storage.

TEST PROCEDURES

Compression Tests on Individual Timbers

One-Stage Compression Tests. The one-stage compression tests on individual timbers *were* designed to show comparative properties of full- sized oak and Douglas fir timbers, both old and new. Douglas fir was tested only as a 15.2 x 35.6 cm (6 x 14 inch) cross section. Oak was tested as 15.2 x 35.6 cm (6 x 14 inch) and 30.5 x 35.6 cm (12 x 14 inch) cross sections to compare size effects. The length of all individual timbers was 121.9 cm (48 inches).

After applying an initial load of 1,340 N (3 kips), the Baldwin Test Machine head was stopped for a close-up photograph of the end of the timber that showed the grid. Loading was then applied at a rate of 13,400 N (30 kips) per minute. Load versus deflection data points were recorded at 30 second intervals by a computer to produce a load versus deflection plot on an x-y plotter for each LVDT while loading progressed.

The computer also recorded the load and deflection at each data point for each timber, then computed the FSPL and the MOE.

A second photograph was taken at 1.3 cm (0.5 inch) deflection, usually past the FSPL. Additional photographs were taken after deflections of 2.5 cm (1 inch) and 3.8 cm (1.5 inches). For timbers that were 30.5 cm (12 inches) thick, a photograph was also taken at the 7.6 cm (3 inch) deflection.

After testing all of the individual timbers in this manner, the load versus deflection plots were examined to determine the proportional limit (yield point) for each timber.

Two-Stage Compression Tests. Two-stage compression tests were performed on individual timbers. These timbers were six Douglas fir and six oak, and all measured 15.2 x 35.6 x 61.0 cm (6 x 14 x 24 inches). Initially each specimen was loaded to a point just above the apparent proportional limit (as observed during development of the stress-strain curve). The following day the specimens were loaded to destruction.

Compression Tests on Layered Timbers

A series of compression tests was run on layers of drydocking timbers to compare with results for individual timbers and to observe the effects of compressive loading without the concrete portion of a typical keel block. Five tests were performed on single layers (of three timbers) of new oak, old oak, and new Douglas fir. Compressive tests were also made on three-layer configurations of new Douglas fir and old oak.

Compression Tests on Composite Block Build-ups

To represent the properties of standard docking blocks encountered at Navy shipyards, ten standard Navy composite build-ups were assembled. Five were formed using new timbers and five using old timbers. The Puget Sound Naval Shipyard furnished ten concrete blocks from their operating inventory for this purpose. These were identified as half pier blocks, each consisting of a steel reinforced concrete block measuring 106.7 cm (42 inches) wide by 121.9 cm (48 inches) long and 38.1 cm (15 inches) high. On the bottom of each concrete block were three 15.2 x 35.6 x 121.9 cm (6 x 14 x 48 inch) oak timbers attached by stud bolts and countersunk nuts.

Composite blockbuild-ups consisting of concrete blocks combined with oak and Douglas fir timbers were assembled to a

nominal 145 cm (57 inch) total height, as shown in Figure 5. The total height of wood in each composite block was a nominal 106.7 cm (42 inches).

3 pcs 6 x 14 x 48 inch fir
3 pcs 12 x 14 x 48 inch oak
4 pcs 12 x 12 x 42 inch oak
3 pcs 6 x 14 x 48 inch oak
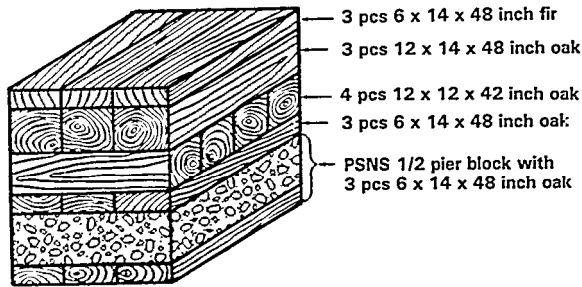PSNS 1/2 pier block with 3 pcs 6 x 14 x 48 inch oak

Figure 5
Composite Block Build-Up
As Tested

None of the concrete blocks was new; therefore, the five appearing to be in the best condition were assigned to be used with new timber, and the remaining five were assigned to tests using old timbers. The oak timbers attached to the bottom of the concrete blocks were old in both the new and old test series. Sixteen individual timbers were selected, checked for moisture content, and positioned in layers above the concrete, as shown in Figure 5. The thickness of the timbers within a layer was matched as closely as possible in order to provide uniform loading over the entire area. Thus, the assembled build-up contained two layers of three 15.2 x 35.6 x 121.9 cm (6 x 14 x 48 inch) oak timbers, one layer of four 30.5 x 30.5 x 106.7 cm (12 x 12 x 42 inch) oak timbers, one layer of three 30.5 x 35.6 x 121.9 cm (12 x 14 x 48 inch) oak timbers, and a capping layer of three 15.2 x 35.6 x 121.9 cm (6 x 14 x 48 inch) Douglas fir timbers.

In testing the composite build-up, a 4,480 N (10 kips) pre-load was applied, then loading progressed at a rate of approximately 35,900 N (80 kips) per minute. Load and deflection data points were recorded at 30 second intervals. When the proportional limit was reached, the rate of loading was increased and controlled by deflection at approximately 1.0 cm (0.4 inches) per minute and continued until the total deflection of the composite reached 10.2 cm (4 inches). The load was then slowly released and the build-up was allowed to relax for two minutes, then reloaded to 4,480 N (10 kips) to measure and record "set".

Load versus deflection data for each block build-up were processed by a computer. During the compression testing, a load versus deflection curve was plotted. The computer also listed each data point, selected the proportional limit (calculated as FSPL, psi) and determined the MOE (calculated from deflection as strain, inch per inch)

for the straight line portion of the curve below the proportional limit.

TEST RESULTS

Individual Timber Results

One-Stage Compression Test Results. Figure 6 shows a series of line drawings traced from photographs of one end of-a new 30.5 x 35.6 cm (12 x 14 inch) oak timber during a compressive test. Note that distortion and failure begin in the area of the pith -- marked with a cross in the left center in Figure 6a. Also note the "X" shape of shear in the end-section in Figure 6c. This "X" shape was characteristic of all test specimens. Figure 7 shows the stress-strain curve for the timber photographed in Figure 6.

Table 1 shows the summary of the FSPLs for the one-stage compressive tests perpendicular to the grain on full-size drydocking timbers by species, sizes, and age categories. Table 2 is the summary of MOEs for the same specimens.

Several observations can be made from the above two tables. The first observation is that the aver- age FSPL compressive strength values for new oak and Douglas fir are lower than the bearing test data shown in the *Wood Handbook* for green white oak 4,620 kPa (670 psi) and green Douglas fir (coast), 2,620 kPa (380 psi) (5). This probably at least partly ref-lects the method of testing *(Wood Handbook* data is derived from test- ing small clear specimens in con-trast contrast to the full-size timbers with various defects and growth characteristics of the present study).

Secondly, it can be observed that the coefficients of variation (COV) for the data are generally in the normal range for clear wood specimens except for the old oak of 30.5 x 35.6 cm (12 x 14 inch) dimensions. Average COV for FSPL perpendicular to the grain in wood is 28 percent [5]. The generally higher COVs of old oak and Douglas fir are likely because some of the old materials, while weathered, had not been used extensively, if at all, and others had been used heavily and contained more checking and perhaps some decay.

Finally, one can observe that the larger dimension 30.5 x 35.6 cm (12 x 14 inch) oak timbers in general are not as strong in compression as the 15.2 x 35.6 cm (6 x 14 inch) oak timbers. This is particularly true for the old timbers.

Figure 8, which shows the stress-strain curves for the ten old Douglas fir timbers included in Tables 1 and 2 above, provides a more graphic view of the variability in the old category of timbers.
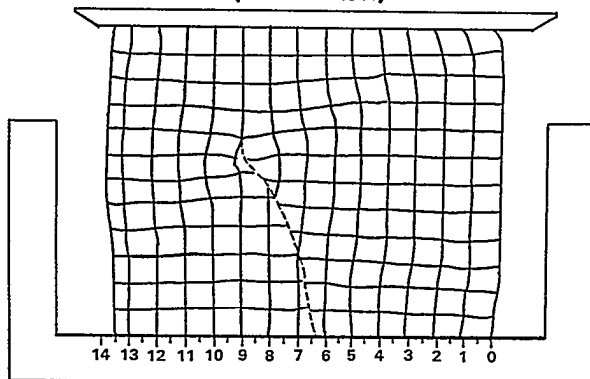
Comparison with Previous Tests. Selected results are available from the Forest Products Laboratory testing of timber keel blocks that were obtained from the Philadelphia Navy Yard (4).
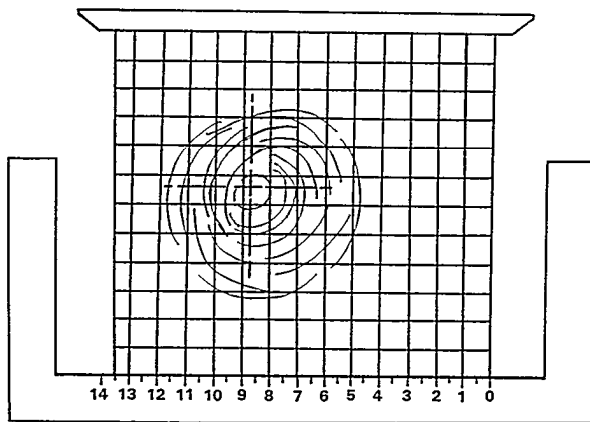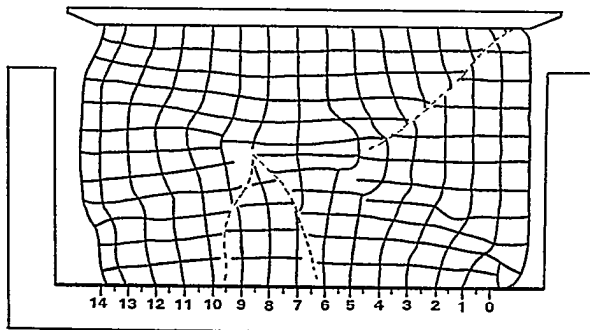
a. Initial Preload (No Strain)

b. 1 Inch Deflection
(850 psi Stress, 0.08 Inch/Inch Strain)

3 Inch Deflection
(Approx 1230 Psi stress, 0.25 Inch/Inch Strain)

Figure 6
End View of Failure Progression in a
12 x 14 Inch Oak Timber
During Testing

Figure 7
Stress-Strain Curve for Oak Timber,
12 x 14 x 48 inches, Loaded Perpendicular
to the Grain (See Also, Figure 6)

Table 1. Summary of Compression Tests on Individual Timbers, FSPL (psi)

| | | Species | | | |
	Size	Oak 6" x 14"	Oak 12" x 14"	Oak Avg.	Douglas Fir 6" x 14"
New	N	15	15	–	15
	A	35.88	39.86	37.57	26.45
	R	21.5-55.84	31.04-49.79	–	26.3-39.0
	S	8.80	5.4	–	7.17
	COV	24.5%	13.5%	–	27.0%
Old	N	15	15	–	10
	A	29.88	21.64	25.76	18.59
	R	15.13-45.83	6.57-56.58	–	4.3-24.0
	S	9.14	13.75	–	6.04
	COV	30.6%	63.5%	–	32.5%
Average of averages		32.9	30.45	31.67	23.31

N = Number of tests   A = Average or mean
R = Range of values   S = Standard deviation
COV = Coefficient of variation

Table 2. Summary of Compression Tests on Individual Timbers, MOE (ksi)

| | | Species | | | |
	Size	Oak 6" x 14"	Oak 12" x 14"	Oak Avg.	Douglas Fir 6" x 14"
New	N	15	15	–	15
	A	567	487	527	328
	R	522-710	389-570	–	263-390
	S	113.75	58.8	–	39.0
	COV	20.1%	12.1%	–	12.2%
Old	N	15	15	–	10
	A	561	410	486	405
	R	241-821	257-784	–	279-570
	S	153.6	138.9	–	131.70
	COV	27.4%	33.7%	–	32.5%
Average of averages		564	449	506	359

Table 3 presents representative FSPL and MOE values that resulted from tests of individual 35.6 x 35.6 x 48.3 cm (14 x 14 x 19 inch) "minor specimens" of docking block timbers. These specimens were loaded in compression perpendicular to the grain.
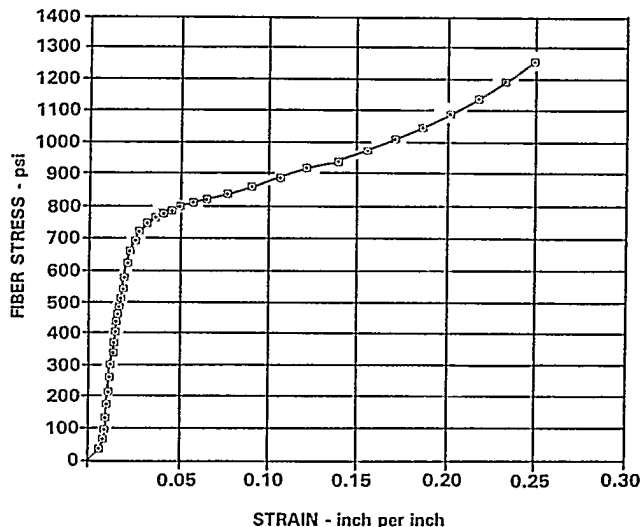
Two-Stage Compression Test Results. The results of the two-stage compression tests on six new timbers of each species are shown in Table 4.

The FSPL and MOE values of the first tests in Table 4 are similar to results

for new timbers shown in Tables 1 and 2. The second loading resulted in higher FSPLs and much lower MOEs. This suggests the significantly different keel block performance that may occur if blocks are composed of timbers that contain new timbers along with those that have been stressed beyond the proportional limit. The effect of a series of such loadings, each above the proportional limit, was not studied in this project.

Pooled Compressive Strength Data. Two other experiments on compressive strength of individual full size drydock timbers were carried out for other purposes. These additional compressive strength data were added to the data from Tables 1 and 2 to increase the sample size. Table 5 presents the pooled data for old and new timbers of both species, regardless of cross section dimension.
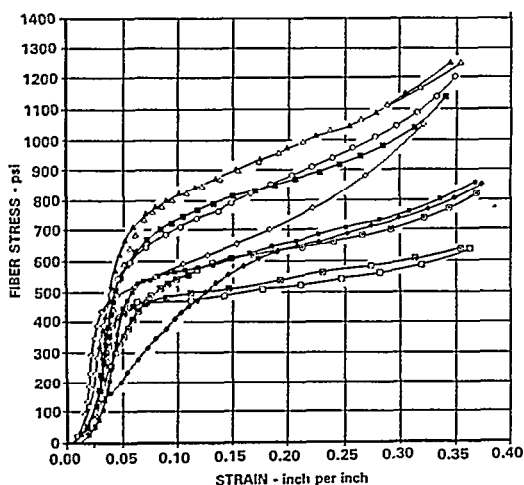

Figure 8
Stress-Strain curves *for* Douglas Fir (Old), 6 x 14 x 48 inches, Loaded Perpendicular to the Grain

Table 3. Test Data From Philadelphia Navy Yard Oak Timbers

Block Set	FSPL (PSI)	MOE (PSI)
1	298	37,725
2	336	40,535
3	395	47,795
4	301	34,790
5	299	39,475
Average	326	40,064
Range	298-395	34,790-47,795

The data in Table 5 shows the range in values that can be expected from randomly selected timbers in Navy shipyards. It is apparent that there is

Table 4. Two-Stage Compressive Tests on New oak and Douglas Fir Timbers

FSPL (psi)	Oak		Douglas Fir	
	1st Loading*	2nd Loading**	1st Loading*	2nd Loading**
N	6	6	6	6
A	596	689	328	444
R	490-673	485-895	258-421	315-461
S	64.1	144.9	56.5	7.2
MOE (ksi)				
N	6	6	6	6
A	35.48	19.86	26.67	8.05
R	10.6-47.9	12.93-26.80	13.46-35.58	5.85-10.4
S	9.87	5.00	7.83	1.64

* Each specimen loaded to slightly above proportional limit and then pressure released and specimen removed from testing machine for 24 hours.
** Specimens re-loaded to destruction.
N = Number of tests   A = Average or mean
R = Range of values   S = Standard deviation

not a large difference between FSPL for old and new timbers, but there is a significant difference in MOEs between the old and new. This indicates that the stiffness of individual timbers and, therefore, entire keel block assemblies, may vary substantially in service and fail to uniformly distribute the load of the ship.

Layered Timber Results

The results for the layered timber strength in general were similar to strength values of individual timbers of the same species and age. There was no obvious enhancement of collective strength from forming layers. It was anticipated that as the number of timbers in the assembly increased, the variation of strength properties between test assemblies would decrease. This was not the case with these data, which may have been due to a limited number of tests. These tests did suggest that there is no assurance that the performance of a combination of timbers is any more predictable than for individual timbers.

Table 5. Pooled Data for compressive Tests on Individual Timbers

Species	Age	No. of Specimens	FSPL (psi) Ave.	Range	MOE (ksi) Ave.	Range
Oak	Old	30	486	241-821	11.4	6.6-56.7
Oak	New	36	539	322-710	37.2	19.6-49.8
D. fir	Old	10	405	279-570	18.6	4.3-24.0
D. fir	New	39	367	258-663	26.8	11.4-38.6

Composite Block Build-Up Results

Composite Block Build-Up Compression Test Results. Results of the tests of the ten composite block build-ups are shown in Table 6. Given that the blocks are comprised of a combination of Douglas fir and oak and that all blocks have an attached layer of old oak, the FSPL and MOE results appear consistent with the results of previous tests on individual timbers and layers of timbers. That is, the FSPL and MOE values of the blocks are

intermediate between values determined for oak and Douglas fir that were determined separately *for* old and new timbers (see Tables 1 and 2). Also, as noted above, the difference between FSPL for old and new timbers is not great. Individual timbers and blocks made entirely of old timbers are lower in strength on average, but strengths of individual timbers, and in this case blocks, may overlap -- some old blocks are stronger than some new blocks.

The most notable feature of the data in Table 6 is the difference between MOE for old and new blocks. The average MOE of the old blocks *is* less than half that of the new blocks, and the lowest MOE of the new blocks is almost one-third higher than the highest of the old blocks. The keel block compressive test data are less variable within each group than the data for individual timbers. The coefficients of variation for the tests in general are less for the blocks than for the sets of individual timbers (see Tables 1 and 2) as might be expected from the number of individual timbers included in each block.

timber blocks and Table 9 contains data on old timber blocks.

The configurations of all the blocks were not the same. At least three of the DTRC blocks had "hard caps," assumed to be oak, and four had "soft caps," which were assumed to be Douglas fir, the same as on all ten of the blocks tested in this study. The averages and ranges of deflections and the "apparent" MOEs for the three tables are shown together in Table 10.

The average test results for the DTRC blocks fall between the averages of the old and the new blocks tested in this study, but are closer to the old block values.

The difference in performance under load between the old and new blocks is evident in Figure 9 which presents the stress-strain curves for all ten of the blocks tested in this work. The lower five curves with less slope are the old blocks. These curves show the higher MOEs of new timbers and the greater variability of the old timbers. They also show that the old timbers can carry loads almost as high as new timbers, but

Table 6. *Summary* of Compressive Tests on Composite Block Build-Ups

New Oak Blocks, New Douglas Fir Capping

							Average	Range	std. Dev.	COV(%)
FSPL (psi)	530	387	410	390	518	499	387-530	73.97	16
MOE (ksi)	36.41	42.54	36.86	38.97	29.8	36.92	29.8-42.5	4.66	13

old Oak Blocks, Old Douglas Fir Capping

							Average	Range	Std. Dev.	COV(%)
FSPL (psi)	304	383	356	400	411	371	304-411	42.72	12
MOE (ksi)	16.59	20.18	19.64	12.58	12.95	16.39	12.6-20.2	3.58	22

Comparison with Previous Tests.
Naval Ships Technical Manual Docking Instruction (NSTM 997) (10) contains a section on "Stress-Strain Characteristics of the Dock Blocks." That section cites deflection data under compressive loads for eight blocks from the Norfolk Naval Shipyard as determined by the David Taylor Model Basin (now David Taylor Research Center, DTRC). Based on that data, Table 7 was constructed.

Although the height of the wood in the present study is 106.7 cm (42 inches) (see Figure 5), the cross section of 106.7 x 121.9 cm (42 x 48 inches) is the same as that of the DTRC block. Therefore, for purposes of comparison, Tables 8 and 9 were calculated for the ten medium blocks tested in this study. Wood height and load were assumed to be the same as for the DTRC tests: 85.1 cm (33.5 inches) wood height and 3,450 kPa (500 psi) load the deflection for each block at the 3,450 kPa (500 psi) load was determined from stress-strain curves for each block. Table 8 contains data *on* new

for the same load, deflections are over twice as great.

Discussion of Wood Strength Variations

It is apparent from the data presented above that the Compressive strengths of individual timbers and composite block build-ups are variable. To one unfamiliar with wood, but used to working with concrete and steel, such variations in wood strength may seem surprisingly large. For example, in Table 5, the FSPL for oak varies from 1,660 to 5,660 kPa (241 to 821 psi). This strength variation is far outside that of any single type of steel or concrete. To better understand these wood strength variations, the following paragraphs describe six major causal factors. These factors include moisture content; specific gravity: botanical and commercial classifications; defects: timber cross section proportion: overloading timbers in service; and

Table 7. Tests on DTRC Composite Build-Ups as Reported in NSTM 977

CAP TYPE	NOT REPORTED	HARD CAP	HARD CAP	HARD CAP	SOFT CAP	SOFT CAT	SOFT CAP	SOFT CAP
CAP HEIGHT. IN.	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
TOTAL WOOD HEIGHT, IN.	33	33.5	33.5	33.5	33.5	33.5	33.5	33.5
CAP LOAD WIDTH x LENGTH, INCHES	42X48(1)	36 IN SP(2)	36 IN SP(2)	36 IN SP(2)	36 IN SP(2)	36 IN SP(2)	48x42(3)	48x42(3)
APPLIED LOAD. KIPS	1000	1000	1000	1000	1000	1000	1000	1000
sTREss, PSI (4)	496	496	496	496	496	496	496	496
BLOCK COMPRESSION, INCHES	1.32	0.67	1.11	1.28	1.49	1.74	1.01	1.12
APPARENT MODULUS OF ELASTICITY (5)	12,400	24,300	14,969	12,981	11,152	9,549	16,451	14,836

(1) DESCRIPTION OF THE TEST DID NOT INDICATE THAT LOAD WAS APPLIED OTHER THAN OVER THE ENTIRE 42 X 48 INCH AREA.
(2) LOAD WAS APPLIED THROUGH A 36 INCH WIDE PLATE BY 42 INCHES.
(3) LOAD WAS APPLIED OVER ENTIRE 42 X 48 INCH AREA.
(4) APPLIED LOAD DIVIDED BY 42 X 48 INCHES (2016 SQ. INCHES)
(5) APPARENT MODULUS OF ELASTICITY (AMOE) CALCULATED FROM STRESS DIVIDED BY STRAIN ASSUMING A STRAIGHT LINE BETWEEN 0 AND 496 PS ALTHOUGH THE FIBER STRESS AT PROPORTIONAL LIMIT (FSPL) OF SOME TIMBERS MAY HAVE BEEN EXCEEDED.
(6) WOOD IN COMPOSITE BLOCKS WAS ASSUMED To BE WHITE OAK EXCEPT FOR CAP: -OAK, SOFT=DOUGLAS FIR. AGE OF WOOD NOT INDICATED.

Table 8. Compression Tests on Composite Block Build-Ups, New Wood

FIVE COMPOSITE BLOCKS CCOMPOSED OF NEW WOOD (1)

CAP TYPE (2)	SOFT	SOFT	s o w	SOFT	SOFT
CAP HEIGHT, INCHES	6	6	6	6	6
TOTAL WOOD HEIGHT, INCHES (3)	33.5	33.5	33.5	33.5	33.5
CAP LOAD WIDTH x LENGTH, INCHES	42 x 48(4)	42 x 48(4)	42 x 48(4)	42 x 48(4)	42 x M(4)
APPLIED LOAD, KPS (5)	1008 KIPS	1008 KIPS	1008 KIPS	1008 KIPS	1008 KIPS
STRESS, PSI (6)	500	500	500	500	500
BLOCK coMPRessIoN, INCHES (7)	0.61	0.61	0.66	0.62	0.73
APPARENT MODULUS OF ELASTICITY (8)	27,682	27,689	25,557	26,855	22,995

(1) THE TIMBERS IN THE BUILD-UP BELOW THE CAP WERE NEW OAK EXCEPT THE 6 X 14 X 48 INCH OAK ON BOTTOM OF CONCRETE WERE SOT NEW.
(2) SOFT CAPS WERE NEW DOUGLAS FIB.
(3) WHEN TESTED, NOMINAL. WOOD HEIGHT WAS 42 INCHES: FOR COMPARISON WITH CH-997 TESTS, HEIGHT WAS CALCULATED AS IF 33.5 INCHES FOR BLOCK COMPRESSION.
(4) THE ACTUAL DIMENSIONS OF EACH BUILD-UP WERE USED DURING TESTING; LOAD WAS APPLIED OVER ENTIRE AREA.
(5) APPLIED LOAD VARIED ACCORDING TO ACTUAL LOADED AREA OF EACH COMPOSITE BUILD-UP.
(6) STRESS CALCULATED FROM ACTUAL LOADED AREA AND APPLIED LOAD.
(7) CALCULATED FROM THE APPARENT MODULUS OF ELASTICITY FOR EACH BLOCK AS IF WOOD HEIGHT WERE 33.5 INCHES.
(8) CALCULATED AS STRAIGHT LINE BETWEEN 0 AND 500 PSI.

Table 9. Compression Tests on Composite Block Build-Ups, Old Wood

FIVE COMPOSITE BLOCKS COMPOSED OF NEW WOOD (1)

CAP TYPE (2)	SOFT	SOFT	SOFT	SOFT	SOFT
CAP HEIGHT, INCHES	6	6	6	6	6
TOTAL WOOD HEIGHT, INCHES (3)	33.5	33.5	33.5	33.5	33.5
CAP LOAD WIDTH X LENGTH, INCHES	42 x 48(4)	42 x 48(4)	42 x 48(4)	42 x 48(4)	42 x 48(4)
APPLIED LOAD, Kps (5)	1008 KIPS	1008 KIPS	1008 KIPS	1008 KIPS	1008 KIPS
STRESS, PSI (6)	500	500	500	500	500
BLOCK COMPRESSION, INCHES (7)	1.42	1.06	1.19	1.6	1.6
APPARENT MODULUS OF ELASTICITY (8)	11,856	15,796	14,073	10,498	10,492

(1) THE TIMBERS IN THE BUILD-UP BELOW THE CAP WERE NEW OAK EXCEPT THE 6 X I4 X 48 INCH OAK ON BOTTOM OF CONCRETE WERE NOT NEW.
(2) SOFT CAPS WERE NEW DOUGLAS FIR.
(3) WHEN TESTED, NOMINAL WOOD HEIGHT WAS 42 INCHES: FOR COMPARISON WITH CH-997 TESTS, HEIGHT WAS CALCULATED AS IF 33.5 INCHES FOR BLOCS COMPRESSION.
(4) THE ACTUAL DIMENSIONS OF EACH BUILD-UP WERE USED DURING TESTING: LOAD WAS APPLIED OVER ENTIRE AREA.
(5) APPLIED LOAD VARIED ACCORDING TO ACTUAL LOADED AREA OF EACH COMPOSITE BUILD-UP.
(6) STRESS CALCULATED FROM ACTUAL LOADED AREA AND APPLIED MAD.
(7) CALCULATED FROH THE APPARENT MODULUS OF ELASTICITY FOR EACH BLOCK AS IF w00D HEIGHT WERE 33.5 INCHES.
(8) CALCULATED As STRAIGHT LINE BETWEEN 0 AND 500 PSI.

geographic origin.

Moisture Content. The strength of wood increases as the moisture content decreases below the fiber saturation point. The fiber saturation point is the point at which, as wood dries, there is no more moisture in cell cavities and moisture starts to be lost from cell walls, causing shrinkage. The fiber saturation point is usually 24 to 30%, based on the oven dry weight of the wood. Some strength properties will nearly double as wood is dried from the green condition to a "dry" moisture content of 12 percent. In this study, all the timbers tested were above the fiber saturation point, which eliminated this possible variable in comparing the

Table 10. Comparison of Test Data Composite Block Build-Ups

property	DTRC Blocks	New BIOCkS	Old Blocks
Average deflection e496/500 psi (in.)	1.2	0.65	1.37
Range of deflection (in.)	0.67-1.79	0.61-0.73	1.06-1.6
Standard deviation	0.301	0.051	cl.243
Average apparent MOE (psi)	14,642	26,156	12,543
Range of MOE (psi)	9,549 to 24,900	22,995 to 27,689	10.492 to 15.796
Standard deviation	4,668	1,970	2,334

strength of timbers. In drydock use, where timbers are close-packed in storage and re-wetted frequently, most timbers can be considered to be above the fiber saturation point.

Specific Gravity. In general, the strength of wood increases as its specific gravity increases. That is, high density woods are usually stronger than low density woods. Note, however,
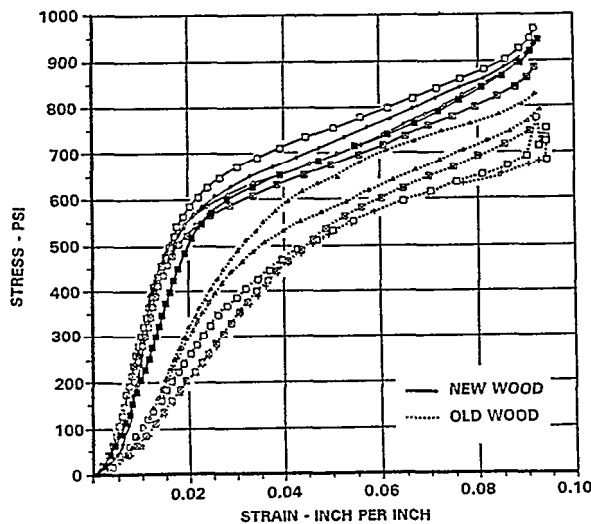
Figure 9
Stress-Strain curves for
Composite Block Build-Ups

that specific gravity alone cannot be used to predict a strength property of an individual timber or species.

Botanical and Commercial Classifications. A factor that may contribute to variations in strength properties of drydocking timbers is the

difference between similar species. Oaks, for example, are divided into two general types -- white oaks and red oaks. The white oaks, being less permeable and thus more durable, are preferred for drydocking timbers. Within each of these divisions are several species with different strength properties. Note in Table 11 that the first three oaks are white oaks and the last three are red oaks.

Table 11. Examples of Variations *in* Specific Gravity and Strength Among Some Oaks (5)

species	specific Gravity (green)	compression Perpendicular to the grain (psi)
White Oak	0.60	670
Chestnut oak	0.57	530
swamp white oak	0.64	760
No. red oak	0.56	610
So. red oak	0.52	550
Black oak	0.56	710

Defects. Strength properties in the *Wood Handbook* (5) are based on tests of small, clear, straight-grained specimens. Usually, wood of this quality cannot be obtained in larger pieces, particularly in those sizes used for drydocking timbers. The incidence of knots, splits, sloping grain and decay all may detract from strength. One or more of these defects can account for some reduced strength of the old timbers in the tests of this study.

Cross Section Proportion. In Tables 1 and 2, which compare 15.2 x 35.6 cm and 30.5 x 35.6 cm (6 x 14 inch and 12 x 14 inch) timbers, it can be *seen* that oaks with the 15.2 x 35.6 cm (6 x 14 inch) cross section generally have higher FPSL and MOE values (with one exception in the MOE of new 30.5 x 35.6 cm (12 x 14 inch) oak timbers). It is suggested that this difference is partially explained by the influence of the height of the specimen with respect to its width. In his work on Poisson's ratio of wood in transverse compression, Bodig (16) observed that the height/width ratio had a strong effect on the apparent Poisson's ratio. The *greater* the height of the specimen *in* relation to its width, the greater was the opportunity for the specimen to bulge in the middle section as the load is applied, while friction at the upper and lower surfaces prevents its lateral

displacement. Specimens with a greater height/width ratio had higher Poisson's ratios and lower FSPL and MOE values.

Further, the larger 30.5 x 35.6 cm (12 x 14 inch) timbers all have pith within the cross section which contains wood that is not as strong as in outer portions. Note in Figure 6 that the failure in the timber begins in the pith area which was typical for individual timbers in this study.

Overloading in Service. The variability of old timbers, individually or in a composite build-up, is usually greater than for new timbers, and the strength of the old timbers is usually less. Some of this variability in a group of timbers, particularly evident in the low MOE values, is probably attributable to previous instances of excessive loading that exceeded the timbers' FSPL. We suggest that as timbers are cross-stacked in layers, adjacent timbers nay differ significantly in MOE. Therefore, no timber carries the sane unit stress along its full length. Consequently, when load is applied to the entire surface of a layer of three or four timbers, the greatest load at the intersected bearing area will be absorbed by the timbers with the highest MOE and perhaps exceed their proportional limit. If such high MOE timbers are relocated, other areas along their length may be similarly affected until their overall load carrying capacity is reduced.

Table 4 demonstrates how strong the effect of exceeding the proportional limit during loading can be on the subsequent stiffness of the timbers. This effect is also suggested in the reference on investigation of drydocking of three aircraft carriers (15), where the highly stressed sternmost keel blocks did not share the load with blocks just forward of them after docking was complete.

Geographic Origin. A minor factor for some commercially important and widely distributed woods is their geographic origin. For most species this is not a consideration and is not a factor in acquiring wood for structural purposes. But Douglas fir is an exception; its strength properties differ for wood originating in "coast" and "interior" regions of the U.S. For example, the average strength in compression perpendicular to the grain for coast Douglas fir is 2,620 kPa (380 psi); for interior Douglas fir it' is 2,900 kPa (420 psi) [5]. The cause of this type of strength variation nay be associated with genetic differences between the woods.

CONCLUSIONS

Briefly, we have drawn the conclusions that follow.

1. Transverse compressive strengths of oak and Douglas fir timbers are variable and this must be considered along with the average strength for drydocking uses.
2. Old (previously used) timbers are more variable in compressive strength properties than new timbers both in FSPL and MOE, but are not necessarily weaker in FSPL. This suggests that although the average unit stress on keel blocks may have been within the recommended limits, stresses on individual timbers may have exceeded FSPL and produced a lowering of MOE.
3. Average FSPL of timbers tested in this study, although slightly lower, compare favorably with published strength values in the *Wood Handbook* (5).
4. The average MOEs of old timbers and other timbers compressed beyond their proportional limits are much lower than MOEs of new timbers, but their load carrying capacity is not damaged.
5. Variations between composite block build-ups are less than between individual timbers.
6. The compressive strength properties of the blocks tested by DTRC were comparable to the blocks made of old timbers tested in this study, which suggests the data presented here is a fair representation of the keel block population.
7. The compressive strength properties of the individual timbers from the Philadelphia Navy Yard (4) were comparable to the strength properties of the individual timbers of the present study, although the Philadelphia timbers have a somewhat lower FSPL (perhaps because of their higher cross section) and a higher MOE than did the timbers of the present study.

IMPLICATIONS FOR NAVY DRYDOCKING

What follows are the implications of this study for Navy drydocking.

1. The variability in compressive strengths of existing keel blocks requires conservative assumptions in anticipating average keel block loads.
2. To avoid "hard spots," which result in localized excessive loads, it is necessary to provide sufficient height of wood build-up in keel blocks. The theoretical calculations of Table 12 show the effect of varying wood height on the resulting average keel block load.
3. Because the strength properties of oak and Douglas fir overlap, the use of Douglas fir as a soft cap should be re-examined. Better load distribution could be obtained with a layer of a lower MOE wood.

Table 12. Theoretical Keel Block Loads for Equal Deflection and Two Heights of Wood

Total Deflection (inches)	18-inch Wood Height			36-inch Wood Height		
	Unit Strain (in./in.)	MOE* (psi)	Load (psi)	Unit Strain (in./in.)	MOE* (psi)	Load (psi)
0.5	0.028	12,000	336	0.014	12,000	168
0.5	0.028	20,000	560	0.014	20,000	280
0.5	0.028	40,000	1120	0.014	40,000	560

*Assumed average MOE for timbers in the keel block.

4. Replacing 30.5 x 35.6 cm (12 x 14 inch) timbers with 15.2 x 35.6 cm (6 x 14 inch) timbers would gradually improve the average strength of keel blocks. (However, high quality 30.5 x 35.6 cm (12 x 14 inch) timbers under the keel would improve lateral distribution of the load from the keel.)

5. Except for very obvious physical damage or decay, the strength of keel block timbers cannot be determined by visual observation. A nondestructive device for testing timber stiffness could help eliminate weak timbers and improve predictability of keel block performance if timbers of comparable stiffness were placed in the same layer.

6. When old timbers are replaced, new timbers should be placed in blocks as a complete layer and preferably at the same level in each keel block so that individual timbers are protected from excessive loads and keel blocks gradually assume more uniformity over time.

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