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NAVY YARD, WASHINGTON, D.C.

AN ANALYSIS OF A FAILURE OF KEEL BLOCKS IN A DRY DOCK

BY LIEUT. COMMANDER E. L. GAYHART, (CC), U. S. N.

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BUREAU OF
CONSTRUCTION AND REPAIR
NAVY DEPARTMENT

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U.S. Experimental Model Basin
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GENERAL

On May 28, 1924, the U.S.S. SOUTH CAROLINA was docked in number 3 drydock at the Navy Yard, Philadelphia, the dock being pumped down and the keel blocks sighted at 2:39 P.M. At about 7:45 A.M. the following morning, or about seventeen hours later, the entire system of keel blocking collapsed under the ship, causing the vessel to fall astern and vertically some three feet in each direction.

The ship, which was one of the battleships scheduled to be scrapped under the Limitation of Naval Armament Treaty, had just previously been used as a target in certain underwater explosion experiments and was docked at this time to permit inspection of the damage resulting from these tests.

Previous to these experiments, the ship had been in the same dock along with other ships from October 24, 1923 until undocked on May 23, 1924. On April 17, 1924 she was undocked and redocked to permit an interchange of the vessels. When redocked on May 28, 1924, she was landed upon blocks similar to those upon which she had rested from April 18 to May 23. During the entire stay in dock, preliminary work was carried out on the SOUTH CAROLINA as well as on the other vessels in connection with scrapping them, and in addition, certain experimental structural features were incorporated into the hull of the SOUTH CAROLINA for test in the underwater explosions just mentioned.

Immediately following the accident an investigation was conducted which ascertained certain facts as to the condition of the ship on docking such as the displacement, draft, and trim, the probable distribution of weight in the ship, the number and distribution of keel blocks and other pertinent information.

From consideration of testimony, the Board of Investigation concluded that the displacement on docking was 16,628 tons and that at the time of the accident the weight on the blocks had been reduced to 15,604 tons by the discharge of water ballast. The ship when docked had a draft aft of 29'3", draft forward of 28'-10" with mean draft of 27'-6-1/2" and had no list.

The Board ascertained that the ship was supported in the dock upon some 320 sets of keel blocks, of which 192 were under the center line keel, 20 under the forward inner docking keels, 69 under the main docking keels, 19 under the outer docking keels, and 20 under the after inner docking keels. The center line keel blocks were spaced 2' center to center, the other blocks 4' center to center. All blocks were erected to the same level, 71-1/2 inches above the bearer blocks which were 10" high. The blocks all carried a spruce cap block 4" thick. The total height from cement floor to top of the cap was 85-1/2 inches. This height was greater than usual since in this case, five blocks exclusive of cap block were used above the bearer block rather than the four blocks customary for this dock. The increase in height was made in order to facilitate the structural work carried out on the ship while in dock.

Several days prior to undocking on May 23, the dock was, partly flooded and it then remained flooded until again pumped down on May 28. In consequence, the blocks were subjected to continuous immersion under a head of 25 or 30 feet of water for a period of 10 days prior to the docking on May 28.

After the ship was docked, the blocking was inspected by the docking officer in accordance with the custom. This inspection showed that all of the blocking was apparently in satisfactory condition with the exception of one block, the second forward of the after knuckle. Testimony before the Board also revealed that the estimated load on the keel blocks upon docking, assuming a uniform weight distribution, was 15.5 tons per sq. ft. If the weights of the forward, midship and after portions of the ship were considered separately, the average pressures resulting become respectively 17.8 tons per sq. ft., 12.2 tons per sq. ft. and 20.3 tons per sq. ft. At the time of the collapse of the blocks, the loss of water ballast had been such as to reduce these figures to 17.2 tons, 12.2 tons and 17.4 tons per sq. ft. respectively.

None of these loads was excessive. In fact the average load was less than the estimated docking pressures that prevail for more recent battleships. With the object of discovering an explanation of the accident, the Bureau of Construction and Repair of the Navy Department initiated a series of tests upon keel blocks removed from this dock.

TESTS ON THE KEEL BLOCKS.

Previous tests have been conducted upon large blocks, particularly at the New York Navy Yard, where keel blocks of the same section as used in this dock were tested three high, but it is not known that an entire assembly of blocks just as removed from the dock has ever been tested before.

It was desired to determine the maximum load that an individual set of blocks would carry and also, the effect upon the capacity of varying the number of blocks in the tier. Ten sets of blocks were selected from number three dock, similar in all respects to the blocks that failed under the ship. Of these ten, five sets were shipped to the Forest Products Laboratory of the Forest Service, at Madison, Wisconsin, and the other five sets to the Bureau of Standards at Washington.

The blocks shipped to Madison were tested under conditions representing a column with one end fixed and the other end free. The material of the blocks was examined for species, moisture content, general condition as to decay, if any, and physical characteristics of small samples.

At the Bureau of Standards, the blocks were only subjected to a compression test, under the loading condition of a column with both ends fixed. A variation was introduced in these tests however, in that certain sets of observations were taken in which the load was held and the change in deflection noted over a period of time.

Tests at the Forest Products Laboratory.

Of the thirty individual blocks comprising the five sets shipped to Madison, all with one exception were determined to be of white oak. The one exception was identified as red oak. The Forest Products Laboratory in commenting upon the quality of this material stated further that the sapwood in the corners of the blocks was in various stages of decay from incipient to material visibly decayed.

In view of the fact that the dock had been flooded for ten days prior to the accident, it was believed advisable to subject the specimen blocks to similar treatment prior to test. Accordingly, upon arrival at Madison, the blocks were submerged in a nearby lake where they were kept pending test. This time of submergence varied from nine days for the first set to twenty days for the last set tested.

As previously described, the action at failure of the blocks consisted in the ship moving parallel to itself astern and at the same time dropping. All of the blocks appeared to pivot at the bearer block, with the top of the block describing a circular arc of radius equal to the block height. This action may be recognized from the photographs (Plate I). From this feature of the failure, it was regarded as one hypothesis that the blocks failed as columns having a fixed base and with the upper end free.

The tests at Madison were conducted on this supposition. In support of this hypothesis, it was agreed that although each individual block might be regarded as a column with both ends fixed, the fact that all the blocks were tied together by the keel of the ship, simply imposed upon each block the condition that the load would always be applied vertically, in other words, was the equivalent of exact centering of the load upon the column, or eliminated any eccentricity. The fact that the ship was free to move longitudinally made all of the blocks free ended columns, and the soft spruce cap reduced or destroyed any resistance to bending moment at the tops of the columns.

Proceeding upon this assumption, the various sets of blocks were set up on the bed of a high testing machine capable of accommodating a timber 20 inches square and 12 feet long between the specimen and the moving head of the machine. The arrangements are shown in Plate II. The set of blocks was bolted to the bed of the machine simulating the attachment of the bearer block in the dock. A roller bearing at each end of the 12 foot timber permitted the top of the set to move sidewise. The length of the timber was considered sufficient to give a practically vertical loading. The load was applied to the cap block through a metal plate 20 inches square and 3-5/8 inches thick. (It should be noted that the top block was 4 feet long and projected 14 inches beyond this plate on each end.)

The position of the roller bearing across the 14 inch width of the top of the block would be adjusted very carefully by screws (to be seen in Plate III). This possibility of careful centering is important to remember when considering some of the results obtained in these tests, for the method of loading consisted in adjusting the centering in repeated trials until a maximum load was obtained. In some cases fifteen trials were made before obtaining what was considered to be a maximum load, and on occasion, a change in this adjustment of less than two hundredths of an inch caused the set to deflect in the opposite direction. Frequently a set would start to deflect in one direction and then as the load was increased, would reverse and finally fail by deflection in the opposite direction. These points are emphasized in order to show that the failure of the blocks in these tests were not due to any transverse component of thrust from the timber through which the load was applied.

It was soon found that the soft spruce cap block crushed unequally and introduced eccentricities thereby reducing the maximum load that might be carried. Dry spruce was substituted but found to be but little better, and finally the tests were carried out with dry birch caps.

The blocks failed in each case by instability of the column without individual failure of any block (except in one case where a block split along a deep season check). Above a certain maximum load, further compression only increased the deflection without increasing the thrust in the block. This type of failure is typical for long columns. The individual blocks, however, were not injured and were immediately used again for a repetition of the test with a set one block less in height.

The sets of blocks in each case were tested under two conditions, first, with all the dogs and clips in place as secured in the drydock, and second, with all dogs and clips removed. There was no consistent difference to be observed in the maximum load carried by the blocks under these two conditions, from which it may be concluded that the dogs and attachment of the bed log do not contribute to the stability of the blocks.

After completion of the tests of the full size assemblies, test specimens 19 inches long were cut from the blocks and subjected to compression tests perpendicular to the grain for determination of the modulus of elasticity of the material and fiber stress at the elastic limit.

A further series of tests was carried out upon model blocks, varying from 1-1/4 inches square to 2 inches square.

The type of failure in the 19 inch pieces is shown in Plate IV. It should be noted that such failures were not produced when the sets were tested as a whole but produced when the individual short sections were tested singly. This point must be borne in mind when considering the results of tests to be described later.

The results of the tests on the complete keel block assemblies are shown in graphic form in Plate V while representative numerical values are tabulated below.

Set	Number of Oak Blocks High	Deflection at Maximum Load (inches)	Maximum Load (Pounds)
F	6	0.16	199500
	5	0.25	251300
	4	0.21	304200
G	6	0.27	175100
	5	0.01	253000
	4	0.09	318400
H	6	0.95	137400
	5	0.24	266800
	4		282800
J	6		100000
	5	0.15	168000
	4	0.02	173000
K	6	0.00	190000
	5	0.22	264000
	4	0.21	317000

The results from the tests of the minor specimens, i.e., the 19 inch specimens are averaged below:

Set	Fiber stress at Elastic Limit Perpendicular to grain	Modulus of Elasticity Perpendicular to the grain	Days Immersion
F	298	37725	20
G	336	40535	18
H	395	47795	13
J	301	34790	9
K	299	39475	16
Average	326	40064	

It will be observed that there is no apparent relation between length of immersion and physical properties.

After the 19 inch minor specimens were cut off, two sets of blocks were built up 6 blocks high ranging in length from 3 feet for the top block to 8 feet for the bed log. These sets were first tested separately in order to center a knife edge upon the top of each. A plate was then placed on the top of the knife edges and the roller bearing previously used was centered and after several trials a maximum load of 215,000 lbs. was obtained.

The two blocks fourth from the bottom were then swung through a right angle to tie the sets together (see Plate VI) and an additional piece inserted in order to give full bearing for the piece fifth from the bottom. Load was then applied with one of the knife edges purposely placed 1 inch off center. This load was stopped at 250,000 lbs. because of crushing under one bearing (no instability however). The knife edge was then centered and the test load was run up to 434,500 lbs. where it was stopped because crushing and consequent inbedding of the bearing interfered with further use of the machine. There was still no sign of failure by instability.

Experiments were conducted on models to test the applicability of the Euler formula and to determine the effect upon the column strength of the increase in length of block from top to bottom of the set. These models were made of selected uniform material for which a careful determination was made of the modulus of elasticity, found to be 87,400 lbs. per square inch perpendicular to the grain. A set of 6 blocks was made, 1-7/8 inches square and 6-1/2 inches long, with a knife edge on the top block. A second set was made with two blocks 6-1/2 inches long, and the other four 9-1/2 inches, 12 inches, 15 inches, and 17 inches long. The first set carried 5460 lbs. and the second set 10,320 lbs.

To calculate the strength of the first set, we may assume the usual (Euler) formula:

$$P = \frac{4\pi^2 EI}{mL^2}$$

Substituting in this formula we have

$$I = \frac{1}{12} \times 6.5 \times \overline{1.87}^3 = 3.542$$

$$L = 6 \times 1.87 + .75 \text{ (knife edge)} = 11.97$$

Since the column has one free end $M = 16$ and

$$P = \frac{4 \times 9.87 \times 87400 \times 3.542}{16 \times (11.97)^2} = 5330 \text{ lbs.}$$

The result by test was 5460 lbs. For the second set, the strength was estimated by considering it equal to the strength of the first set multiplied by a factor obtained by weighting each block for length and distance from the knife edge. The effective length of a block was considered to be the mean length of the trapezoid whose lower base was the length of the block and whose upper base was the length of the block above. This gives for the four stepped blocks effective lengths of 8 inches, 10-3/4 inches, 13-1/2 inches and 16 inches. The knife edge was 3/4 inch high and the blocks 1-7/8 inches square. The derivation of the factor then becomes

1.69 x 1 (unit length = 6–1/2 inches	=	1.69
3.56 x 1	=	3.56
5.43 x (8 ÷ 6.5)	=	6.68
7.30 x (10.75 ÷ 6.5)	=	12.07
9.17 x (13.5 ÷ 6.5)	=	18.83
11.04 x (16 ÷ 6.5)	=	27.15
38.19		39.98

and the factor is $\frac{69.98}{38.19}$

The calculated strength of the second set becomes 5460

$$5460 \times \frac{69.98}{38.19} = 10000 \text{ lbs.}$$

The strength by test was 10,320 lbs.

The significant conclusions reached by the Forest Products Laboratory, quoting freely from their report, are

(a) Oak keel blocks of the size and condition tested, when piled six and five high fall into the Euler class of columns. The four high sets do not.

(b) The maximum load for sets with surfaced blocks having sound, true edges can be accurately calculated.

(c) Wave and decay along the edges of the blocks caused the sets to fail at a lower load than that which they should carry in accordance with their average modulus of elasticity perpendicular to the grain.

(d) When piled six high, the set is quite unstable, requiring exact centering of the load to obtain the maximum value.

(e) Great stability may be obtained by cribbing two or more sets together and such cribbed sets will impart some stability to adjacent uncribbed sets.

(f) Bed log clips, side plates and dogs have no material influence upon the maximum load which a set of the heights tested may sustain.

Tests at the Bureau of Standards.

As already stated, sets of blocks similar to those tested at Madison were submitted to the Bureau of Standards for test. Previous to delivery to that bureau, half of the blocks were submerged under 22 feet of water at the Washington Navy Yard for a period of 11 days. This immersion was with the object of determining a difference in strength, if any, between such soaked blocks, and blocks that had been out of the water since the accident, a period of about five months.

The blocks were tested in a 600,000 lb. capacity testing machine in direct compression with no knife edges or equivalent between the cap block and the moving head of the machine. The method of loading is shown in Plate VII, as well as front and side views of the block assemblies. The load was distributed over the full length of the top block by a steel channel and plate totaling 4-1/2 inches in thickness.

The compression in the blocks was measured by four vertical compressometers placed two on a side of the block and 6 inches from the ends of the top block. These instruments read to .001 inch with a gage length of 66 inches. Lateral deflections in the blocks were measured at mid-height by dials reading to .001 inch.

If we divide the load on the blocks by the area of the top block we obtain the stress in that block, but the strain as measured by the compressometers is not directly applicable for determining the modulus of elasticity, since the blocks are not of uniform length.

The slope of the stress-strain curve is reported below, however, as being the modulus of elasticity, subject to comment to be made later.

The results of these tests are tabulated as follows:

Block	Observed Modulus	Wet or nominally dry	Maximum Load
B	41,100	Dry	600,000
C	51,100	Wet	600,000
A	40,400	Wet	400,000
B	30,600	Dry	400,000
	(Retest after four days)		
E	35,600	Dry	292,000

Keel block "E" failed by splitting along season checks in the three top blocks. All other blocks carried the capacity of the testing machine without failure, although considerably distorted (See Plate VII).

The fifth block, "D" which was an unsymmetrical side keel block was not tested.

The stress-strain curves for these blocks are shown on Plate VIII. The stresses were obtained by dividing the total load by the nominal area of the top block (672 sq. in.) The strains were obtained by dividing the total shortening by the gage length, 66 inches, giving a result in inches per inch. The curvature near the origin of the curve is caused by initial irregularities in the bearing between the several blocks.

Lateral deflections are shown on Plate IX.

It is a recognized property of wood that its capacity for sustaining a load for a long period of time is considerably less than its capacity, for loads over short intervals. This property seemed significant when it is remembered that the accident to the SOUTH CAROLINA occurred after a lapse of some seventeen hours and after the weight on the blocks had been actually reduced by the discharge of water ballast.

Accordingly at the time that set "A" was tested, the stress-strain data were taken up to a load of 400,000, at which point the load was maintained steady and compression readings taken at half hour intervals for a period of 27 hours. During this period, there was a continuous shortening of the set of blocks. This was with a nominal stress (in the top block) of 596 lbs. per sq. in. The curve for the time-strain relations is shown in Plate X on which plate there is also given a plot for the time-strain relations observed in the retest of block "B" over a period of 7-1/2 hrs.

In the case of block "A", the relation between time and strain may be represented by the formula.

d = 0.0068 to 0.316

where d = shortening in inches per inch

t = time in hours.

For block "B" the equation is

d = 0.0049 to 0.266

Further Tests at the Forest Products Laboratory.

In comparing the results of the two sets of tests we note that the tests carried out at the Forest Products Laboratory showed that a set of blocks six high has very little stability when subjected to a stress approaching 300 lbs per square inch under the free-end condition of leading, while similar blocks under "fixed end conditions" at the Bureau of Standards sustained a stress about three times as great without failure by instability.

The blocks at Madison were loaded by a roller bearing at the top, those under the ship and at the Bureau of Standards were loaded by a bearing surface maintained horizontal, and with the pressure applied to a spruce cap block. A question then arises as to the capacity of the spruce cap to resist bending moment in the end of the column, since such capacity determines in part, the difference between the conditions under the ship and at the Forest Products Laboratory.

Additional tests were therefore conducted at the Forest Products Laboratory to determine the effect of continued loading upon spruce. A three inch length of one of the spruce cap blocks was subjected to a compressive test at a rate of about .089 inches per minute, a normal testing speed. The relation between load and compression is shown on curve "A" of Plate XI. A second sample similar to the first was then subjected to a compression test at a rate of .00063 inches per minute, the ratio of the speeds in these two tests being 140:1. The duration of the second test was 42 hours up to a compression of 1.6 inches. The first specimen was compressed by the same amount in 18 minutes. The relation between load and compression in the second test is shown on curve "B" of Plate XI. A comparison of these two curves shows the marked effect of continued heavy loading upon the resistance of this material to compression.

DISCUSSION OF THE TESTS.

When we compare the results of the two sets of tests, it is necessary first to consider the effect of the two conditions of loading upon the strength of the blocks regarded as a column. In each, the bottom of the column may be regarded as fixed. In the one set of tests, there was no lateral restraint for the head of the column while for the other set of tests the top was restrained from motion sidewise. There are accordingly two possibilities for the shape of the deflection curve arising from these different conditions, while each of these possibilities is again doubled depending upon whether bending moment is assumed at the top or not. The resulting four curves are shown in Plate XII, in which Figs. 1 and 2 represent the two cases for the Forest Products Laboratory method of loading, and Figs. 3 and 4, the cases for the method of loading employed at the Bureau of Standards. For each of these cases, the virtual length of the column is expressed in the figure in terms of L, where L is the height from floor of dock to the keel.

When we consider the plastic nature of spruce under load as demonstrated by the curves of Plate XI, it is easy to realize that in the course of a few hours, the conditions represented by Fig. 1 may change to Fig. 2, and those of Fig. 3 to Fig. 4, and even how, in the absence of lateral restraint initial condition represented by Fig. 3 may become converted in the case represented by Fig. 2, with a consequent quadrupling of the virtual column length and attendant loss in stability. Although the sets of blocks have a ratio of height to breadth of but 6:1 and a slenderness ratio of but approximately 20:1, nevertheless, they must be regarded as long columns. The slenderness ratio is not a sole criterion but must be qualified by consideration of the elasticity of the material. The formulas for computing column strength agree in containing a term $\frac{E}{L^2}$. In other words, for the same strength, in so far as these quantities affect the strength of the column, the length may vary inversely as the square root of the modulus of elasticity without affecting the maximum load the column will carry.

The 19 inch minor specimens showed an average modulus of elasticity in compression perpendicular to the grain of about 40000 lbs. per square inch. The virtual modulus of elasticity of this material (to be discussed later) in the blocks, taking account of the reduction in stress with increased length of blocks from top to base is about 72,800. The modulus of elasticity of oak in compression parallel to the grain is in the neighborhood of 1,200,000 lbs. per square inch, or about 16.5 times as much as the virtual modulus of the material we are dealing with. Then, when we compare those columns in their proportions to customary wooden columns we should mentally multiply the height by a factor $\sqrt{16.5}$. That is, these keel blocks 82 inches high, are no stronger than columns of similar section (constant section 48" x 14") having a height of 82 x 16.5 = 333 inches or 27.7 feet, in which the modulus of elasticity is 1,200,000 lbs. per square inch. In fact, because of the lower value of the transverse compressive strength, the keel blocks are actually weaker than the equivalent columns just assumed for comparison.

It is now a matter of interest to calculate the strength of the blocks and make comparison with the test results. Two formulas will be used, the Euler formula mentioned in the Forest Products Laboratory report and an adaptation of the J. B. Johnson formula. This latter formula is a successful empirical formula for steel columns designed to cover the range in length from short columns for which the strength limit is the direct compressive strength of the material to the column length at which the Euler formula becomes applicable. For a discussion of column strength and the use of this formula, reference is invited among other text books to the book "Materials of Construction" by Professor G. B. Upton, Edition of 1916 (John Wiley and Sons) page 96 et seq.

The Johnson formula is based upon the assumption that the limit of strength is reached in a column when the maximum stress reaches the yield point of the material. The formula then represents the strength of a column by a second power parabola tangent to the Euler curve at a point when the stress is equal to half of the stress at the yield point.

Turning now to the reference just cited, the notation employed in that book will here be used. Following that notation the two formulas are:

Euler

$$P_M = \frac{4\pi^2 E I}{M L^2}$$

Johnson

$$P_M = FC\left(1 - \frac{MC}{16\pi^2 E} \cdot \frac{L^2}{K^2}\right)$$

where

P_M = maximum load
F = Area of cross section
K = Radius of gyration of section
I = Moment of Inertia of the section
L = Free length of the column
C = Yield point of material
M = Coefficient determined by end conditions
Both ends fixed M = 1, both ends round, M = 4,
one end fixed, other free M = 16.

The Euler formula endeavors to find the force which will maintain a column in equilibrium between the elastic resistance to bending and the moment of eccentricity of the load. Theoretically, for this critical load, such force is independent of the deflection. Since the formula is derived solely from considerations of elastic resistance to bending, the direct compressive stress is neglected, and the formula gives results that are too high for any but long columns.

The Johnson formula, as stated before, yields results that agree well with experiment up to the point where the Eulei formula applies. Observing the form of the Johnson formula, it will be noted that this formula computes the direct compressive strength for the material and deducts a correction for that additional component of stress arising from deflection and consequent eccentricity of the load. The formula in general is applicable up to that point where the correction becomes equal to 1/2 of the compressive strength. Beyond that point the Euler formula will be found to fit experimental results.

The Johnson formula, as stated above, bases column strength in an empirical fashion upon the yield point of the material. In the case of wood, however, there is no pronounced yield point as recognized with steel. If the elastic limit of wood is used in such a formula, results will be obtained that are far lower than obtained in actual experience. It has been found that the use in such a formula of a stress equal to twice the elastic limit as a virtual yield point gives results consistent with experience. For this suggestion, the writer is indebted to Mr. J. A. Newlin, of the Forest Products Laboratory. In the following discussion the yield point of the material will be taken as 650 lbs. per square inch.

In applying either of these two formulas it is necessary to introduce a correction for the influence of the trapezoidal shape of the pile of blocks.

The correction is made by a factor derived in a similar manner to the factor used in the analysis of the results of the model tests. The derivation of the factor is based upon the assumption that the reduction in stress as the blocks increase in length from top to bottom, with consequent reduction in compression, results in a condition equivalent to that which would exist in blocks of uniform length but proportionate increase in modulus from top to bottom, and also that the component of the deflection at the top of the block arising from compression in any one block is dependent upon the distance of that block from the top. Having obtained such a factor we may multiply the modulus (40,000) of the material by this factor and consider that the deflection and capacity of the set of keel blocks will be the same as in a column of uniform section having this increased modulus.

Subsequent tests at the Forest Products Laboratory have shown that although 40,000 pounds per square inch is the average modulus of elasticity as determined by test of specimens of full cross section and 19 inches long, the value of the modulus influencing column load should be modified to take care of the difference in elasticity at the center and on the outside edges of the blocks. All of the blocks were box heart cuts and there is a material reduction in the modulus near the edges due to the slope of the growth rings. This reduction would be about 1/9 of the average from compression tests and therefore there should be employed a further factor of 8/9 in addition to the trapezoidal factor.

We may now proceed to estimate the capacity of the keel block sets and compare with actual tests.

Substituting in the Euler formula

$$P_M = \frac{4 \times 9.87 \times 40,000 \times 11,000}{16 \times 84^2} = 153,800 \text{ lbs.}$$

Multiplying by the factor 1.82 x 8/9, which is equivalent to the use of a virtual modulus of 64,700 we obtain

$$P_M = 249,000 \text{ lbs.}$$

By test, the average maximum load (excluding set J) is

$$P_M = 175,500 \text{ lbs.}$$

Substituting in the Johnson formula, we have

$$P_M = 672 \times 650 \left(1 - \frac{16 \times 650 \times 432}{16 \times 9.87 \times 64,700}\right) = 437,000 (1 - .440)$$

$$= 245,000 \text{ lbs.}$$

Following a similar procedure for the set 5-high we find

P_M = 259,000 (by test excluding set J)

= 311,000 Johnson-dropping upper block

= 278,000 " " lower "

= 378,000 Euler " upper "

= 317,000 " " lower "

For the set 4-high taking the combination of blocks used in the test of the 6 set, the results are

P_M = 305,600 (by test excluding set J)

P_M = 332,000 Johnson

Upon Plate V, where the results of the tests at Madison are shown graphically there are also plotted the calculated maximum loads listed above, as well as the curves for the Euler and Johnson formulas for the condition that E = 64,700 lbs. per sq. in. This modulus applies to the 6-high set only and it is for this reason that the calculated spots for the 5- and 4-high sets do not fall on the curves. This plate shows that the difference in strength of the several heights of blocks as determined by test is consistent with the calculated strength by formula.

The results by test are somewhat lower than indicated by the formula. This difference is due in part to the arbitrary use in the formula of a yield stress equal to twice the stress at the elastic limit. The lower strength in practice also arises from the fact that incipient decay at the corners reduced the strength and stiffness of the material along the edges with the result that the column strength would be materially reduced even though the average modulus as determined by tests on single blocks would not be perceptibly affected.

Such agreement of test results with formulas as occurs demonstrates both that the test results of the Madison tests are consistent with the physical properties of the material and also that the method of loading followed at Madison correctly represents a column with one end free.

In attempting to apply theory to the blocks as tested at the Bureau of Standards we find that the virtual column length is from 1/2 to 2/3 of the actual length depending upon the degree of fixity given by the spruce cap block. These conditions are illustrated by Figures 3 and 4 of Plate XII. Since the spruce cap block was crushed by the high load to approximately one half of its original thickness it could contribute but little fixity to the top of the column and it is probable that the column was of the type illustrated by Fig. 4. That this was the case is borne out by the deflection evident in the photograph Plate VII. With a virtual length of 2/3 L for this condition as against 2 L for the blocks tested at Madison, it is seen that these columns tested at the Bureau of Standards unquestionably fall into the short strut class, and that they would develop the direct compressive strength of the wood to a point well above the elastic limit of the material. (This was likewise the case of the 4-high sets tested at Madison, although these latter sets failed by instability beyond a certain maximum load, still showing some influence of height upon their capacity. Accordingly, we find the blocks at the Bureau of Standards carrying a load up to the capacity of the testing machine.

It is noteworthy that the stress-strain curves of Plate VIII show a point of tangency at a stress of between 300 and 350 lbs. per square inch, which value is in agreement with the average of the tests reported by the Forest Products Laboratory.

In commenting upon the values of the modulus of elasticity reported by the Bureau of Standards, it should be noted that this modulus was determined and reported from the slope of the stress strain curves. This procedure is subject to the comment that on account of the considerable disparity in stress in the several blocks, it is probable that initially the compression occurred largely in the two upper blocks. The slope of the curves would then largely represent the modulus of the material in the two upper blocks. With this in mind, it is noted that this modulus of elasticity agrees well with the value of the same property as reported by the Forest Products Laboratory.

Application of Test Data to Conditions, under the Ship.

In plate XIII there are given weight curves for the ship. These curves show both the distribution of weight in the ship as designed and also the distribution of weight in the ship at the time she was last docked. This latter weight curve which totals 15440 tons was based upon early information furnished by the Navy Yard at Philadelphia, as being the weight of the ship and ballast upon docking, exclusive of the water which had entered through the openings torn by the underwater explosions. The latter water had free egress and ran out as the dock was pumped down. From estimates as to the displacement upon docking which were submitted to the Board of Investigation it was concluded that the weight upon the blocks at the time of docking was 16,628 tons and that this weight had been reduced to 15,604 tons at the time of the accident. The weight curve of Plate XIII may then be taken as a conservative estimate of the distribution of the weight of the ship at the time of the accident. The weight upon docking was about 1000 tons greater of which some 400 tons was in the forward portion of the ship and 600 tons in the after portion. In addition to the normal and docking weight curves, the weight curve is also shown for the light condition of the ship in order to permit some explanation of the fact that the ship remained securely upon these blocks for several months prior to the final docking and accident.

In constructing the curve for the weight upon the blocks, the effect of the unsupported portions of the ship at the bow and stern is provided for by folding back the overhanging portion of the weight curve for a distance equal to its own length, adding these ordinates to the ordinates of the portion so overlapped. This distribution is rather arbitrary but no satisfactory logical procedure is immediately apparent.

The various portions of the final weight curve break up into segments of more or less uniform weight. The average weight for these several segments was determined, and these averages used for calculating the loads upon the keel blocks.

The ship as has been previously stated was supported on centerline blocks from Frame 6 to Frame 102. These blocks of which there were 192 were spaced 2 feet apart. In addition, there were docking keels extending from about Frame 17 to Frame 92 which keels were supported on blocks spaced 4 feet apart and 128 in number. The displacement of the ship upon docking, i.e., 16,628 divided by the number of the blocks gives an average load per block of about 52 tons. By the time of the accident, this average load had been reduced to about 49 tons.

Owing to the considerable variation in the distribution of the weight of the ship, and also by reason of the overhanging ends of the ship, it is probable that there was a marked variation in the load upon the various blocks. In fact, if the average ordinates for the several subdivisions of the weight curve are taken as indicated on Plate XIII and used to estimate the weights of these subdivisions, such weights when divided by the number of blocks under the subdivision give loads per block as follows:

Frames	Loads per block
6 to 15-1/2	38.4 tons
15-1/2 to 17	32.0
17 to 20-1/2	16.0
20-1/2 to 28-1/2	50.0
28-1/2 to 31	29.4
31 to 38	63.0
38 to 42-1/2	39.6
42-1/2 to 47-1/2	29.4
47-1/2 to 62-1/2	40.6
62-1/2 to 66-1/2	46.0
66-1/2 to 71-1/2	32.6
71-1/2 to 80-1/2	43.6
80-1/2 to 86-1/2	57.8
86-1/2 to 89-1/2	32.4
89-1/2 to 92	51.4
92 to 96-1/2	102.8
96-1/2 to 102	57.6

Actually, no such large variations will occur since the ships structure will distribute the load. However, it is certain that the blocks under generally heavy regions, such as the vicinity of the turrets will be more heavily loaded than those under the region from Frame 38-1/2 to Frame 80-1/2. Also, it is certain that the blocks at the ends of the ship will be heavily loaded, since they can receive support from the adjacent structure from but one direction only.

In commenting upon the large change in load at Frame 92, it should be observed that this change is caused by the fact that the docking keels terminate in the middle of a high intensity of load leaving a considerable portion to be carried by the centerline blocks only. Because of this condition it is probable that the blocks abaft Frame 92 were subjected to loads considerably in excess of the average, though probably not so high as indicated by the above tabulation.

It was estimated that some 600 tons of water flowed out of the after portion of the ship (aft of Frame 81) between the time of docking and the time of the accident. There were 64 blocks under this area with an average change in load of about 9.4 tons per block. The estimate of loads per block must then be increased by about 9 tons to give the load on the blocks (in the stern) when the ship was first docked.

If we examine the tabulation of loads per block in conjunction with the weight curve, we note that the region from Frame 102 forward to Frame 96-1/2 is uniformly loaded, and further, that the region forward of Frame 96-1/2 is even more heavily loaded. We may then conclude that at the time of the accident these blocks were loaded up to at least the calculated amount of 57.6 tons as their own share and even more since they would carry some of the distribution of load from the heavy region forward of Frame 96-1/2.

Considering this heavily loaded region, we find that over some 8 blocks, there is a load of 102.8 tons per block, or about 50 tons per block above the average for the vicinity. Let us say that this represents an excess of 400 tons to be distributed over the blocks from Frame 89-1/2 to the knuckle, about 30 in all. We should then raise the estimate of 57.6 tons for the aftermost blocks by about 13.3 tons making the probable individual load on these blocks just previous to the accident about 71 tons. This estimate should be still further increased by 9 tons for water ballast giving a load per block on docking of some 80 tons which may be considered as the maximum block load.

From Plate V it may be seen that a load of from 70 to 80 tons per block is well into the range of instability for free ended blocks. However, if the heavily loaded blocks are restrained from deflecting by the rigidity of the other blocks near the center of the ship, then very much heavier loads could be carried.

Since the individual loads on the blocks were generally less than their capacity as free end columns it is improbable that the collapse of the keel blocks was due to direct overloads.

Other Influences Affecting the Stability of the Keel Blocks.

When we search for other influences that might have affected the stability of the ship on the blocks there are three possibilities.

First, damage to the ship from the explosions causing change in shape.

Second, damage to the drydock.

Third, effect of trim of ship.

In considering the first influence, that is, possibility of damage to the ship, attention is invited to the profile of the ship on Plate XIII on which there have been indicated the position and extent of the damaged areas following the underwater tests. From this plate, (as well as actual knowledge of the effect of the explosion) it is apparent that the explosions did not destroy main structural members, and that the ship's longitudinal strength was not seriously reduced. It is not likely then that any deflection resulted in the ship, as a consequence of the explosions, at least to such an extent that the stability of the blocks was affected. It should be noted that the loads per block tabulated in the preceding section were based upon conditions much more severe than any damage the ship may have sustained, for the estimate of these loads assumed that no shearing stresses were transmitted between sections.

The experiments were conducted while the ship was moored in the river parallel to the channel, opposite the dock entrance, and about 650 feet from the caisson of the dock. The explosive charges were set off upon the opposite side of the ship from the dock, the ship being swung after the first explosion. The dock was consequently in what might be called the shadow of the ship and, considering this fact and the distance from the explosion, it is not probable that the explosions caused any damage to the blocks that later resulted in the accident. No damage was evident, either to the dock or the blocks at the time the observers inspected the ship immediately after pumping down.

Probable Explanation of the Accident.

The explanation of the accident probably lies in the combination of circumstances that the ship was docked with a drag and that she was so landed as to bring the stern knuckle of the keel upon a single block rather than upon the solid blocking in the south end of the dock.

Let us examine the loads on the keel blocks between the time the after knuckle first touched and the time when the ship had landed all along the keel. These loads will be estimated upon the assumption that the compression in the blocks is proportional to the load and that therefore the total load taken by the blocks is equal to the number of blocks bearing multiplied by 1/2 the load taken by the block under the knuckle. The compression in the oak blocks is estimated by multiplying the strain in inches per inch from Plate VIII by 80, the height of the oak in inches. The compression in the spruce is estimated by multiplying the ordinates of the upper curve of Plate XI by 10, since this curve represents compression in a piece 3 inches long, while the width of the keel at and near the knuckle was 30 inches.

The draft of the ship on docking was 29 feet 3 inches aft and 25 feet 10 inches forward, a difference of trim of 41 inches. The moment to change trim 1 inch was about 1560 tons-feet indicating a total trimming moment of about 64000 tons-feet to bring the ship to an even keel. The distance of the midship section from the knuckle was 184 feet. The resulting upward force required at the knuckle to level the ship on the blocks was then at least 350 tons.

For any intermediate condition of trim we may arrive at the loads on the blocks by a process of trial and error which is carried out by assuming a load on the knuckle block and determining the corresponding compression in the last block, then using this compression and the slope of the keel to determine the number of blocks bearing, we multiply this number by half the load on the last block to find the total load. This total is then compared with the upward force corresponding to the condition of trim. Any discrepancy is then used to correct the guess as to the load on the last block, and the process is repeated until the total upward force is found consistent with the force required to bring to the particular condition of trim. The results of such calculations are tabulated below in two tables. The first of the tables gives the compression to be expected in a block for various loads. The second table gives the estimated load on the knuckle block at various conditions of trim and related information.

Load on Block		Intensity In Oak	Load on spruce lbs. in	Compression in		Total Compression Inches
lbs.	tons	lbs/sq/in.	3 inches	Oak	Spruce	
60000	26.8	90	6000	.22	.10	.32
80000	35.8	120	8000	.26	.18	.44
90000	40.2	134	9000	.28	.23	.51
100000	44.6	149	10000	.30	.30	.60
110000	49.0	164	11000	.33	.35	.68

Remaining Difference in Trim	Slope of Keel Inches in ( ) feet	Force required at stern to change from (Tons)	Assumed load on knuckles block (lbs.)	Compression inches	Feet of Bear-ing.	Blocks	Average Load per block
36	11.7	51	80000	.44	5.2	3	17.9
29	14.1	102	100000	.60	8.5	5	22.3
23	17.7	153	110000	.68	12.3	6	24.5
17	24.0	204	110000	.68	16.3	8	24.5
11	37.8	255	100000	.60	22.7	11(12)?	22.3
5	81.5	306	80000	.44	35.9	18	17.9

In the preceding table, the correctness as to the estimate of the load on the knuckle block (5th column) is indicated by a comparison of the last column with the fourth column, from which it is evident that the estimates contained in the fifth column are consistent and approximately correct.

It appears from this tabulation that as the vessel settles on the blocks, there is a concentrated load on the block at the knuckle ranging from 80,000 lbs. when the trim has changed 6 inches to 110,000 lbs. for a change of trim of about two feet and then declining again as blocks come to bear more rapidly than the trimming reaction increases.

It is desirable at this point to cite again the experience of the Forest Products Laboratory in testing the blocks six-high. They found that the blocks were unstable, that with the original spruce caps it was impossible to obtain any consistent maximum loads because the erratic crushing of the spruce introduced eccentricity in the loading, and that even the substitution of dry spruce for the original spruce caps did not give satisfaction. Consistent maximum loads were only obtained when birch was substituted for the spruce, and even then the sets were found so unstable that variations as slight as 1/50 of an inch in the centering of the roller bearing through which the load was applied would change the direction of the deflection of the column.

In contrast to the laboratory conditions under which the blocks were tested at Madison let us consider the conditions under which the blocks at the stern were loaded as the ship settled down to an even keel bearing. In the first place, the cap blocks were of spruce, the same material that had to be discarded at Madison. Then instead of the precise centering of the load that prevailed at Madison, the slope of the keel caused the load to be applied first at the after edge of the block, 7 inches from the center, and it could not reach the forward edge until sufficient crushing occurred over the remainder of the bearing. Mindful of the very careful adjustment found necessary at Madison in order to develop the maximum strength of the column, it is easily understood that under the extreme conditions of eccentricity imposed by the slope of the keel, the knuckle block would deflect and fail to carry its full strength of 60 to 70 tons indicated by the graphs on Plate V. Furthermore, during the period that the ship is bearing on but a few blocks, there is no question but that these blocks are in the condition of columns with one end free and the data on Plate V applicable.

The slope of the keel, which causes eccentricity in the loading of these columns also predetermines the direction in which they will deflect, namely with the convexity forward since their direction of bending will be such as to tend to bring their top surface into parallel contact with the keel. The ship at this time is not held except by centering lines and by the contact at the knuckle. The effect of the deflection in the blocks will then be to move the ship slightly astern.

Although the load on the block at the knuckle does not change greatly during the process of trimming down, the percentage change in the load on the other blocks is large. This fact is a cause of further instability of the blocks through their interaction. Let us take the case of three blocks bearing. There is a relatively heavy load on the last block, approximately two-thirds as much in the second and about one-third as much in the third. Let us also assume that the tendency of the last block to deflect with the heavy eccentric loading is greater than the rigidity of the two other lightly loaded blocks, particularly in view of the fact that they, also, have their load applied at the after edge. There will result a certain deflection in all three blocks. Now as the water falls and the ship changes trim the pressure on the blocks increases and at the same time a fourth block comes into contact. The load on the last block increases only slightly but the load on the second block increases considerably since it now becomes approximately equal to three-fourths of the load on the last block instead of two-thirds as before. This increase in load on the second block causes it to deflect and exert a further push on the first block while pulling the third and the new fourth. The process continues in this way, with a cumulative deflection in the last block and an induced initial deflection on the blocks farther forward as they come into bearing.

It should be noted that the greatest load on the knuckle block due to effect of trim was 110000 lbs. or 49 tons. This load is only some 25% less than the capacity of these blocks obtained under the most favorable conditions. It is also probable that the effect of the eccentric loading on the block would be to prevent it from taking a very large fraction of its capacity under test conditions, say, not more than half. Then the effect of the process of cumulative deflection just described would be accentuated by throwing more load farther forward where it has less effect on the trim.

It should now be recalled that the keel block forward of the knuckle was observed to be split when the docking officer inspected the ship after docking, which is evidence of some unusual action in this region.

Although in the course of the investigation there was testimony to the effect that all of the blocks were observed to be upright or vertical with no tendency to lean either forward or aft, yet any cumulative deflection such as just described might easily have been overlooked since only a few blocks would be affected. The deflection would not be great since the deflection at maximum load in the case of the blocks tested at Madison was only between 1/4 and 1/2 inch.

After the keel landed all along and the water continued to fall, the weight of the vessel became distributed over all of the blocks and the load reduced at the knuckle but the deflections set up in the blocks near the knuckle would necessarily remain. Finally, with the dock empty, we would come to the distribution of load which was roughly estimated in a previous section. In this estimate it was stated that the loads on the last few center keel blocks were probably 80 tons per block on docking, decreasing to 71 tons just before the accident. These loads which are in the range of instability for carefully centered blocks, would have certainly caused the deflection blocks near the knuckle to collapse except that further deflection was prevented by the effect of the keel in tying these blocks to the stable, vertical blocks under the remainder of the ship.

A condition was produced here, however, which ultimately caused the collapse of the entire block system. This condition was the existence of a fore and aft component in the thrust of the deflected blocks. The astern component of the block reaction was resisted for a time by the stability of the blocks that had not been subjected to the cumulative deflecting process while pumping down, but the stability was only temporary, for it resided in the ability of the spruce caps to withstand differential compression between their forward and after edges and restrain deflection of the vertical blocks. With such a plastic material as the spruce is shown to be, by the curves of Plate XI, it was only a question of a few hours before the steadily applied horizontal component of the reaction of the stem blocks could overcome the stiffness of the spruce cap blocks, convert the keel blocks under them into the equivalent of round-ended columns, pull the tops of these columns over until their load became eccentric, and then there following the collapse of the entire system.

It now remains to explain the circumstance that the ship had been docked before on blocks of this same height in this same dock and had rested on such blocks from October 24, 1923, to April 17, 1924, and from April 18, 1924, till May 23, 1924, without accident. The explanation probably lies in the fact that on the occasion of these previous dockings, the ship was light, even lighter than her designed light displacement by reason of preliminary work that had been done toward scrapping her. Inspection of the weight curve shows that most of the 2000 odd ton difference in displacement between the light condition and her condition when last docked was in the ends of the ship. Such concentration near the ends (ballast water in the magazines) was the cause of the higher loads on the end blocks, and it is to be expected that in the light conditions the load was not only less, but it also was more uniformly distributed. The reduced load per block probably left the blocks with sufficient stability to resist any overturning tendency if such developed.

In support of the foregoing explanation, it is ascertained from the docking records that when docked on October 24, 1923 the drafts were 20'-0" forward, 23'-3" aft, mean draft 21'-7½". These drafts correspond to a displacement of 13,800 tons which was 2800 tons less than her displacement when docked immediately prior to the accident. When docked April 18, 1924 the drafts were 21'-6" forward, 22'-6" aft, mean draft 22'-0". On this occasion, it will be noted the difference in trim was small as compared with the difference in trim when docked on May 28, 1924.

CONCLUSIONS.

The conclusions from the foregoing analysis of the conditions under which the SOUTH CAROLINA was docked and the related tests of dry dock keel blocks are –

1. Keel blocks 6–high when loaded in such a manner that the tops are restrained from lateral deflection will carry loads up to the compressive strength of the material.

2. Keel blocks 6–high when so loaded that the upper ends are free become unstable at loads of about 60 tons and their maximum strength is greatly impaired by eccentricity in the loading.

3. The average load on the blocks on which the SOUTH CAROLINA was docked was less than the load at which the blocks, regarded as free–ended columns would become unstable, eliminating excessive loading as a direct cause of the accident.

4. When the ship was docked with a drag, this condition imposed heavy concentrated loads upon the blocks upon which the keel first landed at the stern, causing these blocks to deflect toward the stern.

5. The initial deflection introduced into the keel blocks at the stern was held as the ship settled down on the blocks all along the keel.

6. The initial deflection that remained in the stern blocks after the ship was docked gave rise to a horizontal component in the thrust exerted by these blocks.

7. The horizontal component of the thrust was resisted by the rigidity of the remaining keel blocks, which, however, depended for their rigidity upon the stiffness of their spruce caps.

8. Spruce under heavy compression is plastic and these cap blocks gradually yielded in such a way as to permit the originally stable keel blocks to deflect under the action of the steadily applied horizontal force.

RECOMMENDATIONS.

1. When occasion requires the use of unusually high keel blocks, insure adequate stability by cribbing a sufficient proportion of the keel blocks.

2. When docking a ship having a drag, land the knuckle of the keel upon blocking sufficiently stable to bear the high concentration of load that occurs during the interval before the keel lands all along.

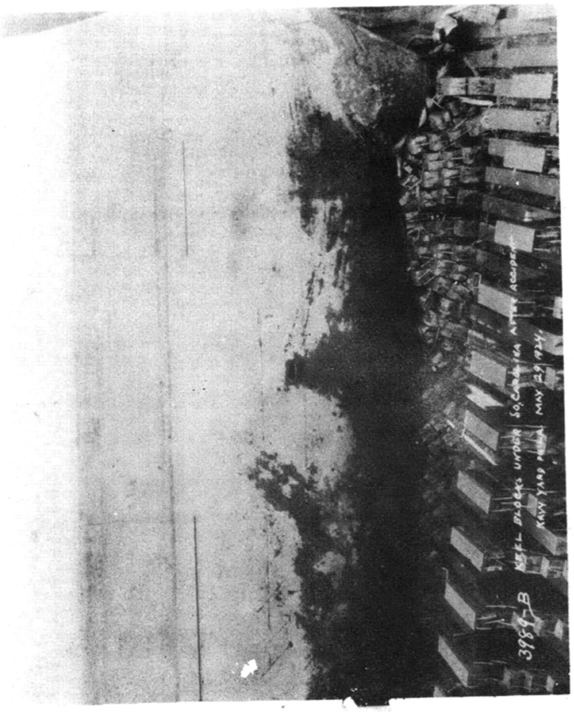
Attention is invited again to the results obtained from cribbing in the tests at the Forest Products Laboratory. By a simple system of cribbing (Plate VI) the maximum capacity of a pair of 6–high sets was raised from 215,000 lbs. to 434,500 lbs., i.e., more than doubled. and the latter load was limited by the local crushing strength of the wood rather than by instability of the blocks. With blocks 6–high, the practice of cribbing alternate pairs of blocks, or perhaps even one–third of the blocks would probably be found adequate.

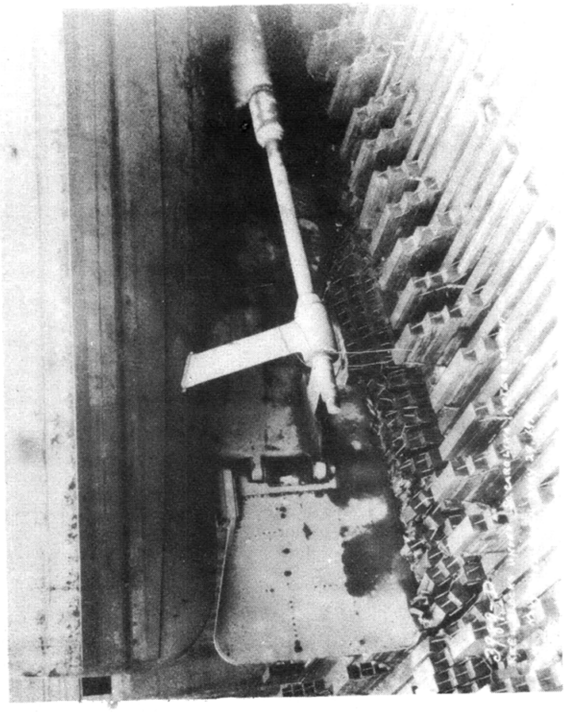
The tests showed that the limit of stability for 5–high sets is between 24 and 25 tons per square feet. The average docking pressure for our capital ships is about 20 tons per square feet, not far from the stable limit for 5-high sets, while the calculated pressures under some portions of the ships may materially exceed the 20 ton figure. Practically all of the new 1000 foot docks use blocking 5-high and it seems advisable to add a further recommendation.

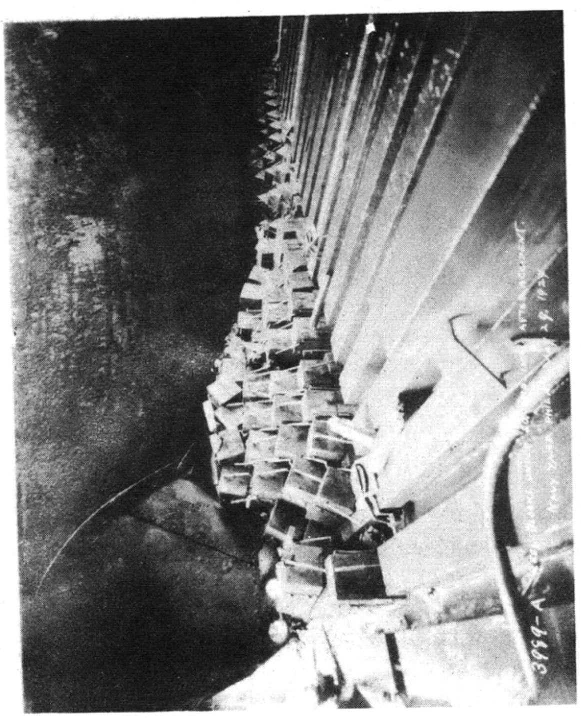
3. In the case of docks where the keel blocks are ordinarily 5-blocks high, insure their stability by cribbing at least 25% of the blocks.

A minor recommendation is repeated here from the report of the Forest Products Laboratory. This recommendation is based upon the emphasis laid by the Laboratory upon the physical condition of the blocks as to incipient and even active decay.

4. Apply some form of preservative treatment to the material of the blocks.







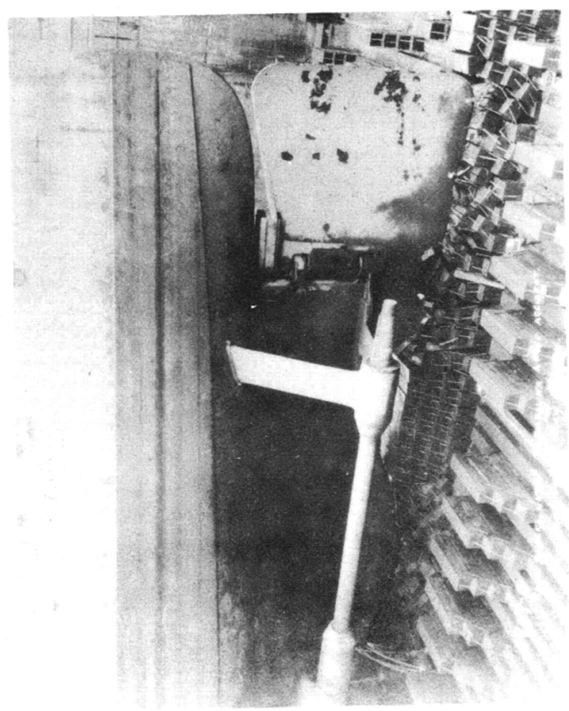


PLATE 1

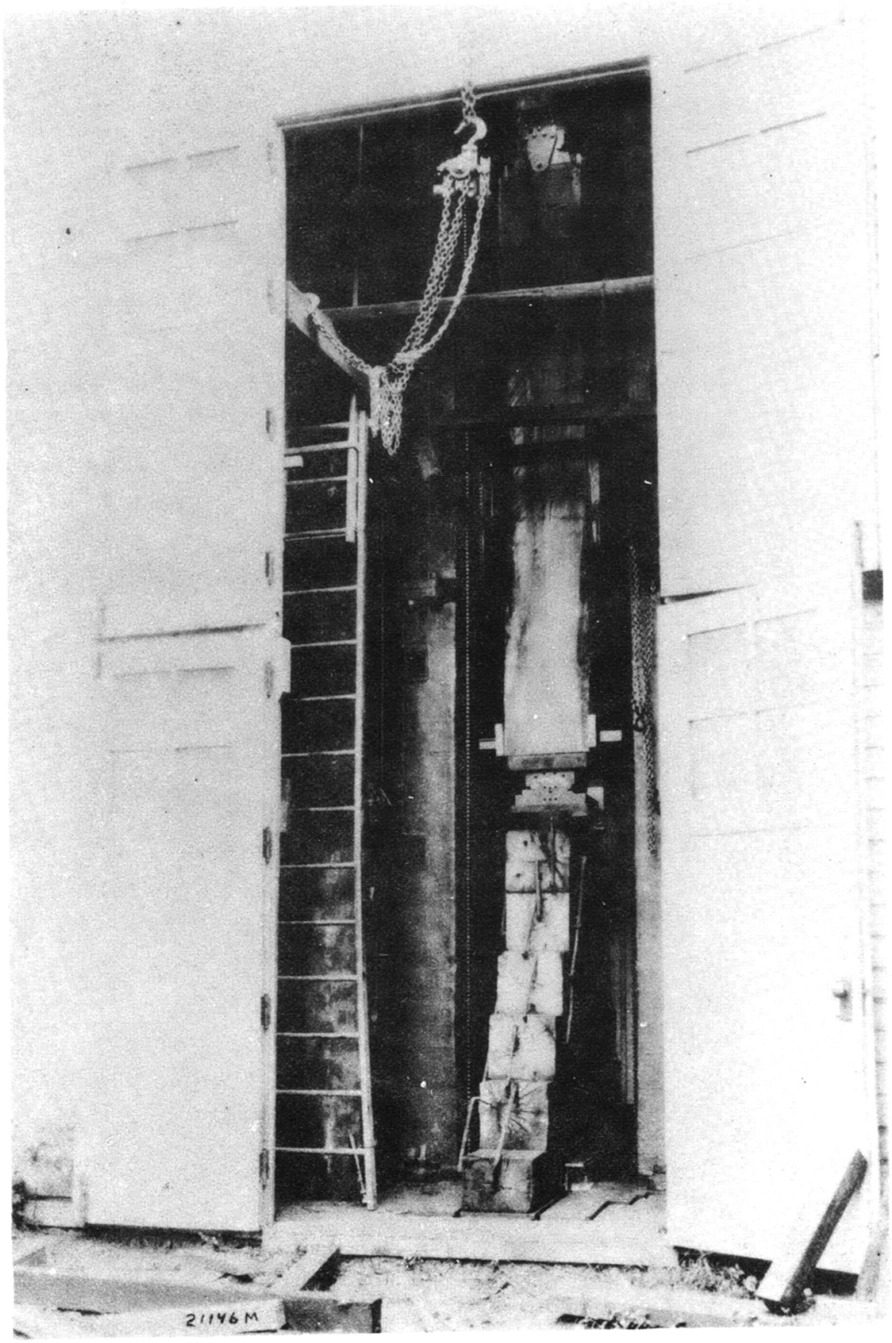


PLATE II

PLATE III

PLATE IV

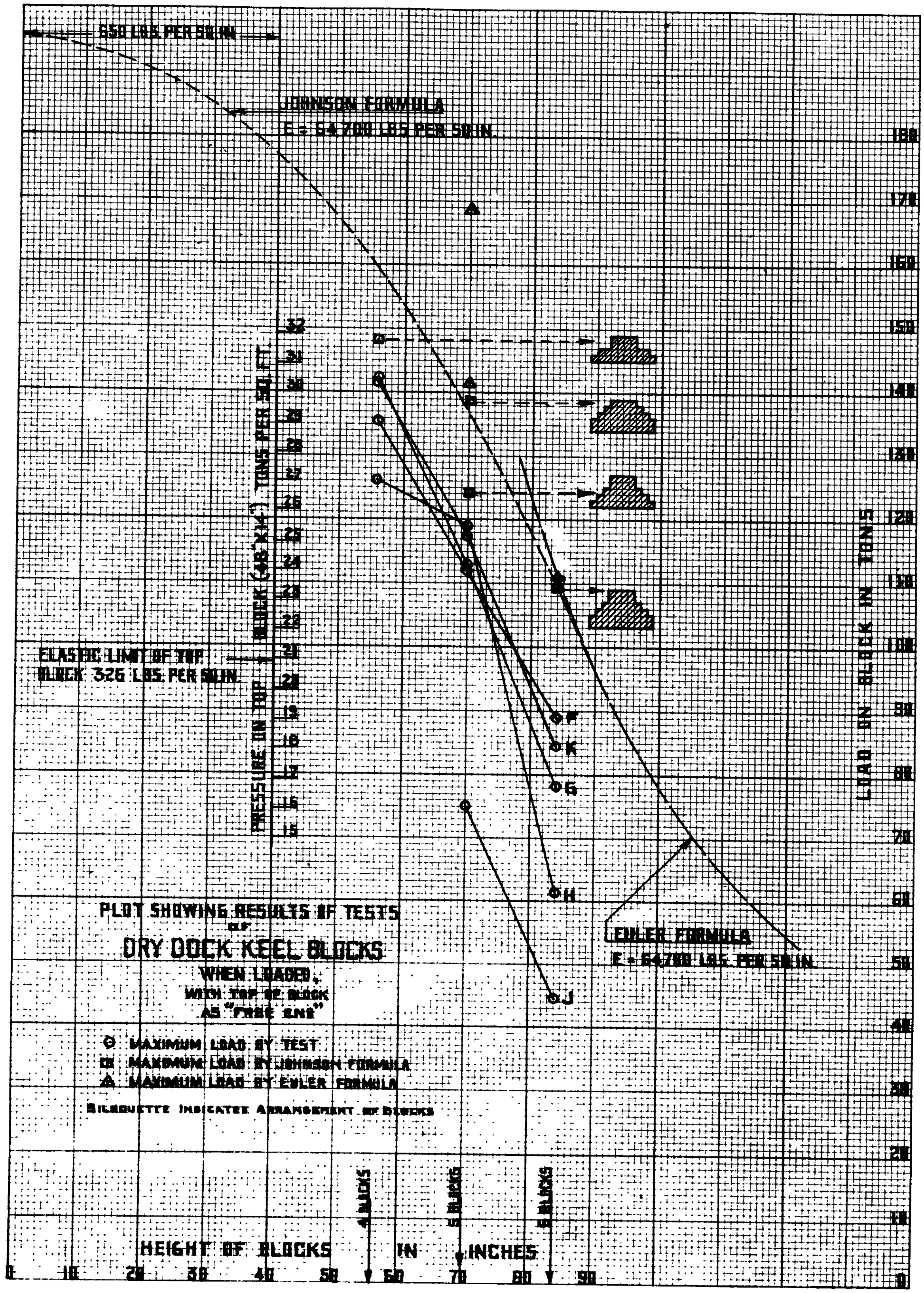
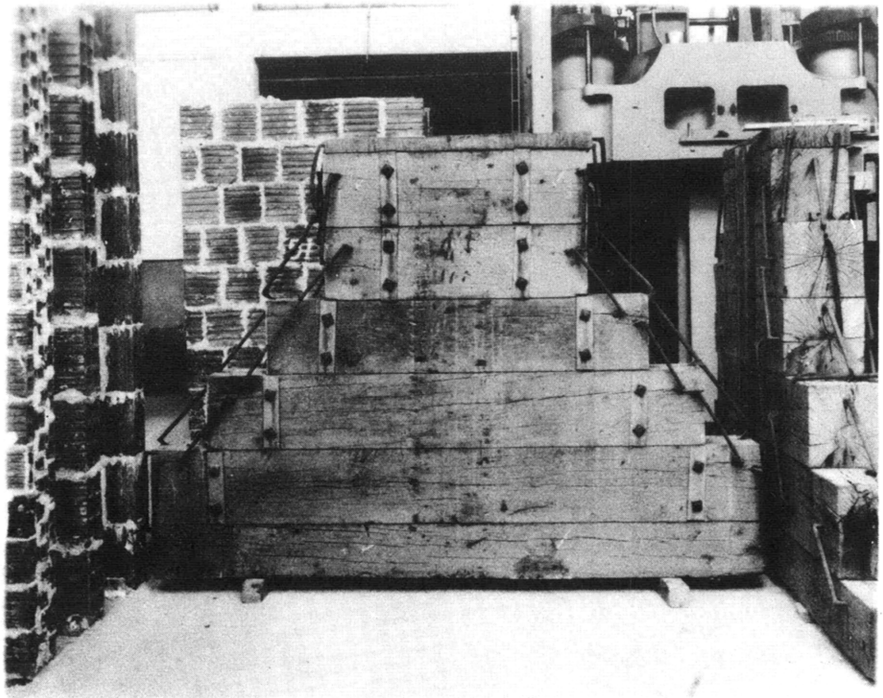
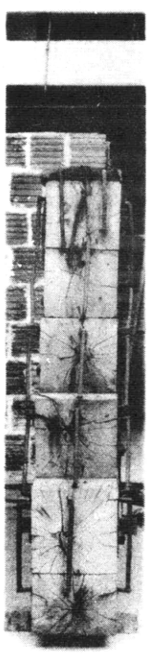

650 LBS. PER SQ. IN.
JOHNSON FORMULA
E = 64 700 LBS. PER SQ. IN.
PRESSURE ON TOP BLOCK (48"X14") TONS PER SQ. FT.
ELASTIC LIMIT OF TOP BLOCK 326 LBS. PER SQ. IN.
LOAD ON BLOCK IN TONS
EULER FORMULA
E = 64,700 LBS. PER SQ. IN.
PLOT SHOWING RESULTS OF TESTS OF DRY DOCK KEEL BLOCKS WHEN LOADED, WITH TOP OF BLOCK AS "FREE END"
MAXIMUM LOAD BY TEST
MAXIMUM LOAD BY JOHNSON FORMULA
MAXIMUM LOAD BY EULER FORMULA
SILHOUETTE INDICATES ARRANGEMENT OF BLOCKS
4 BLOCKS
5 BLOCKS
6 BLOCKS
HEIGHT OF BLOCKS IN INCHES
F
K
G
H
J

PLATE V

PLATE VI





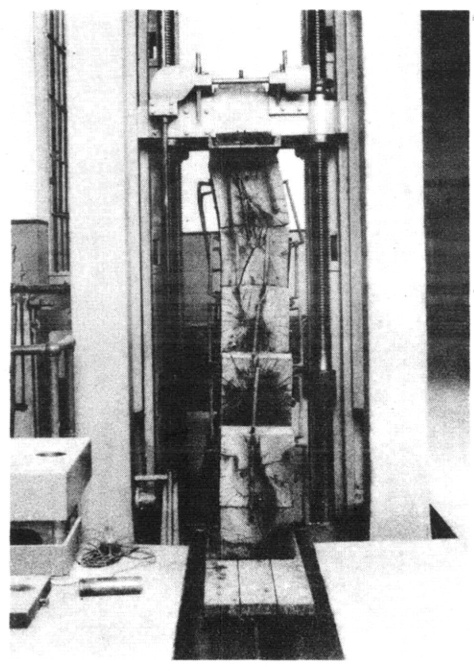
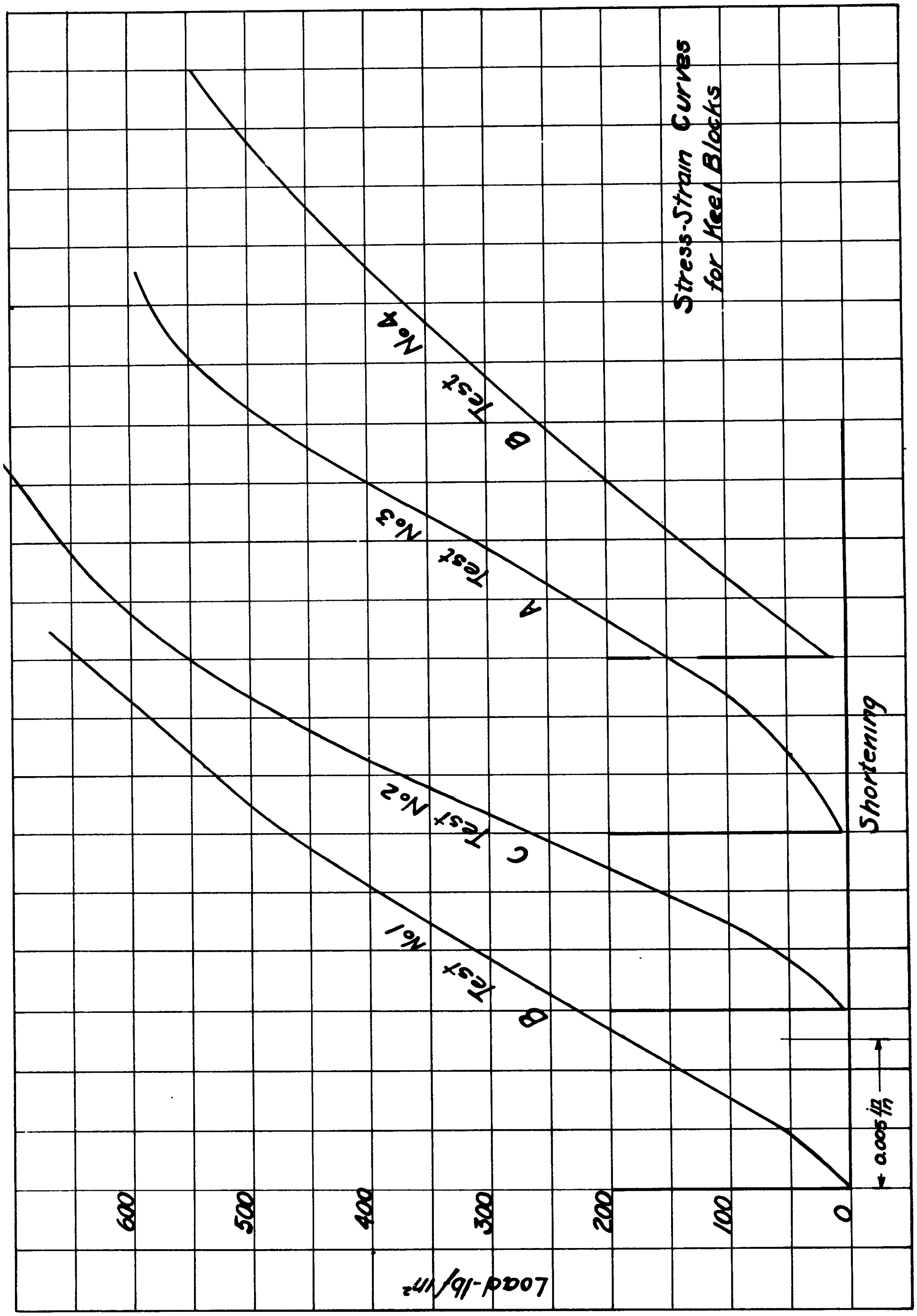


PLATE VII



Stress-Strain Curves
for Keel Blocks
B Test No.4
A Test No.3
C Test No.2
B Test No.1
Shortening
0.005 in
Load-lb/in²
0
100
200
300
400
500
600

PLATE VIII

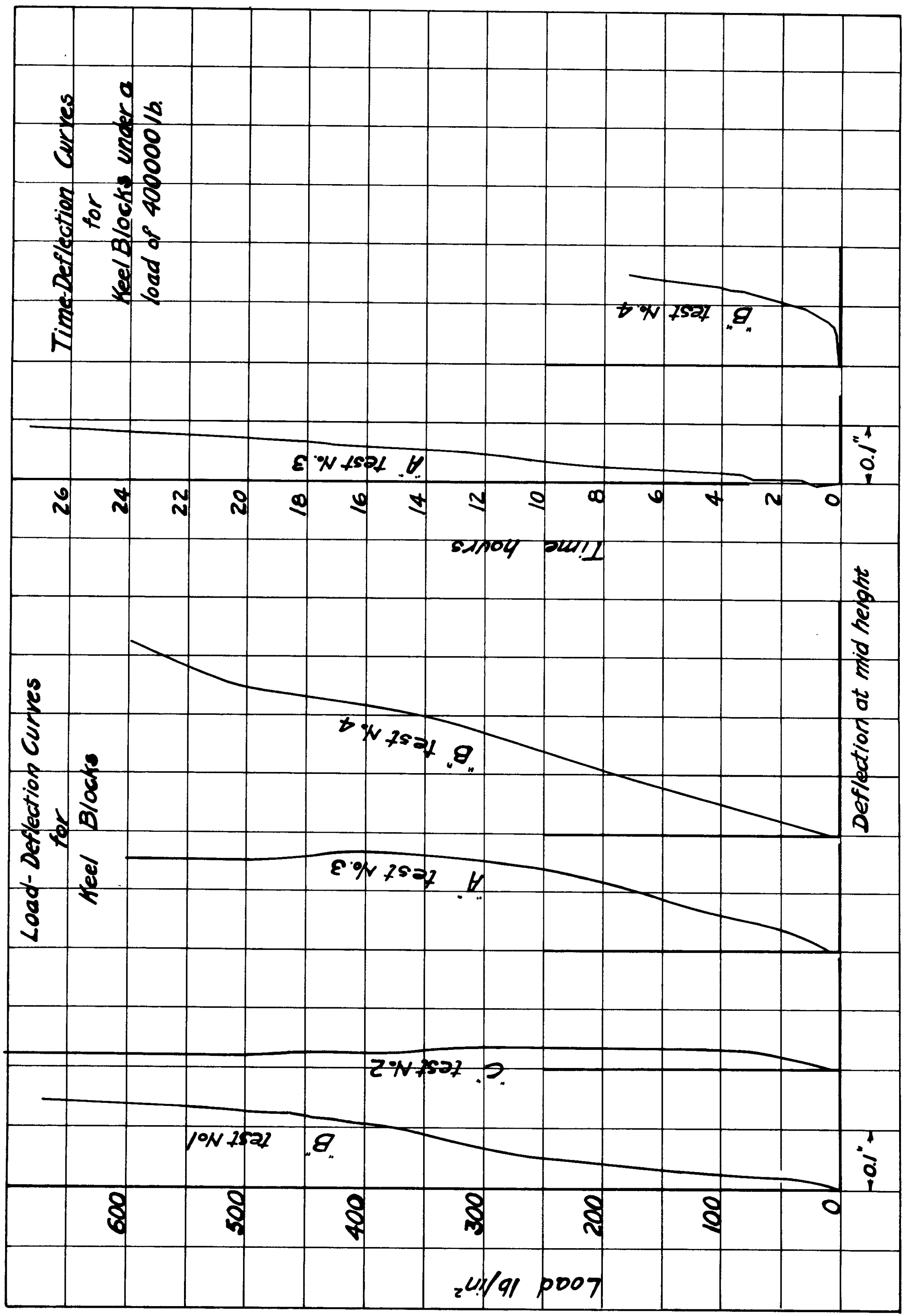
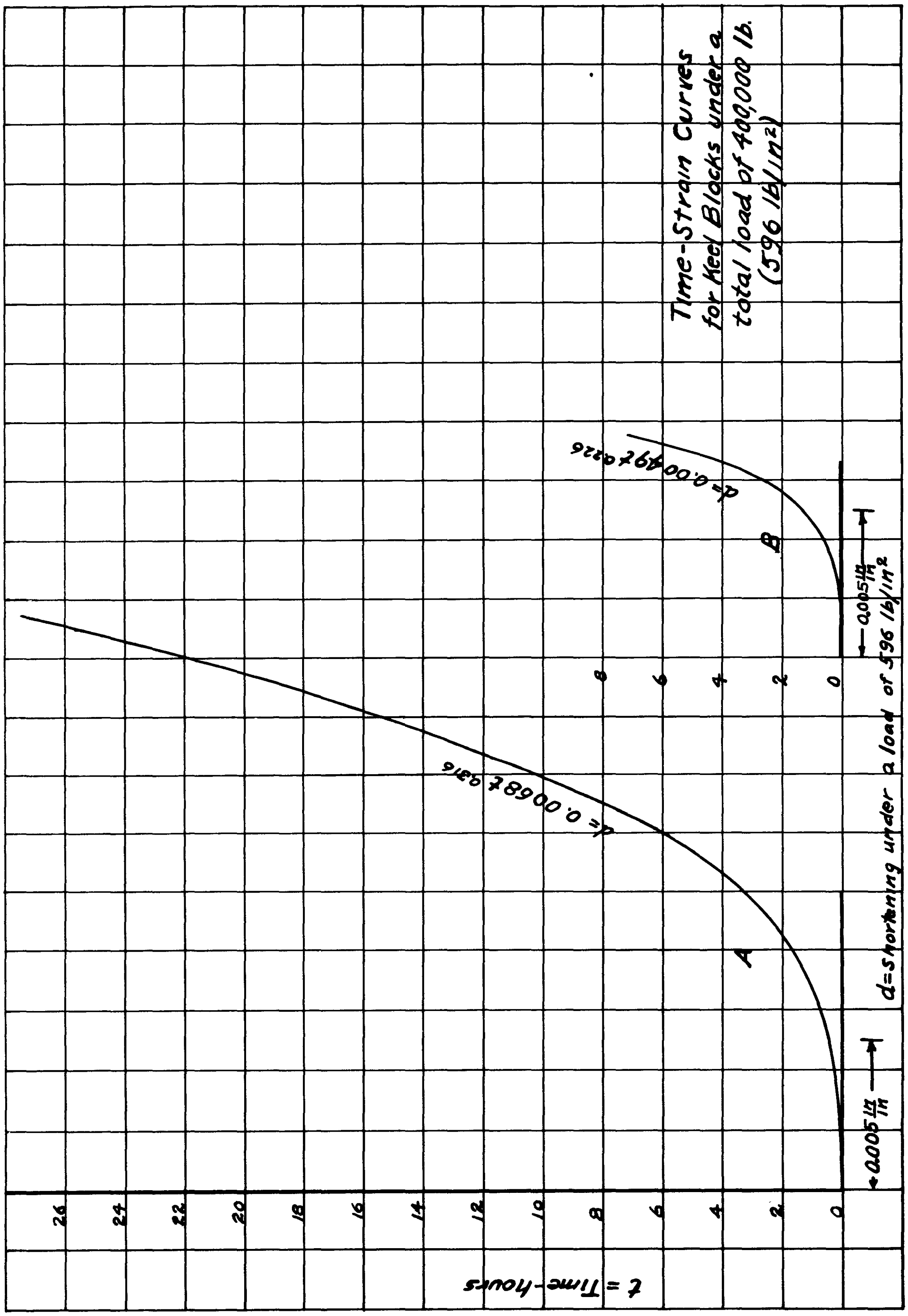
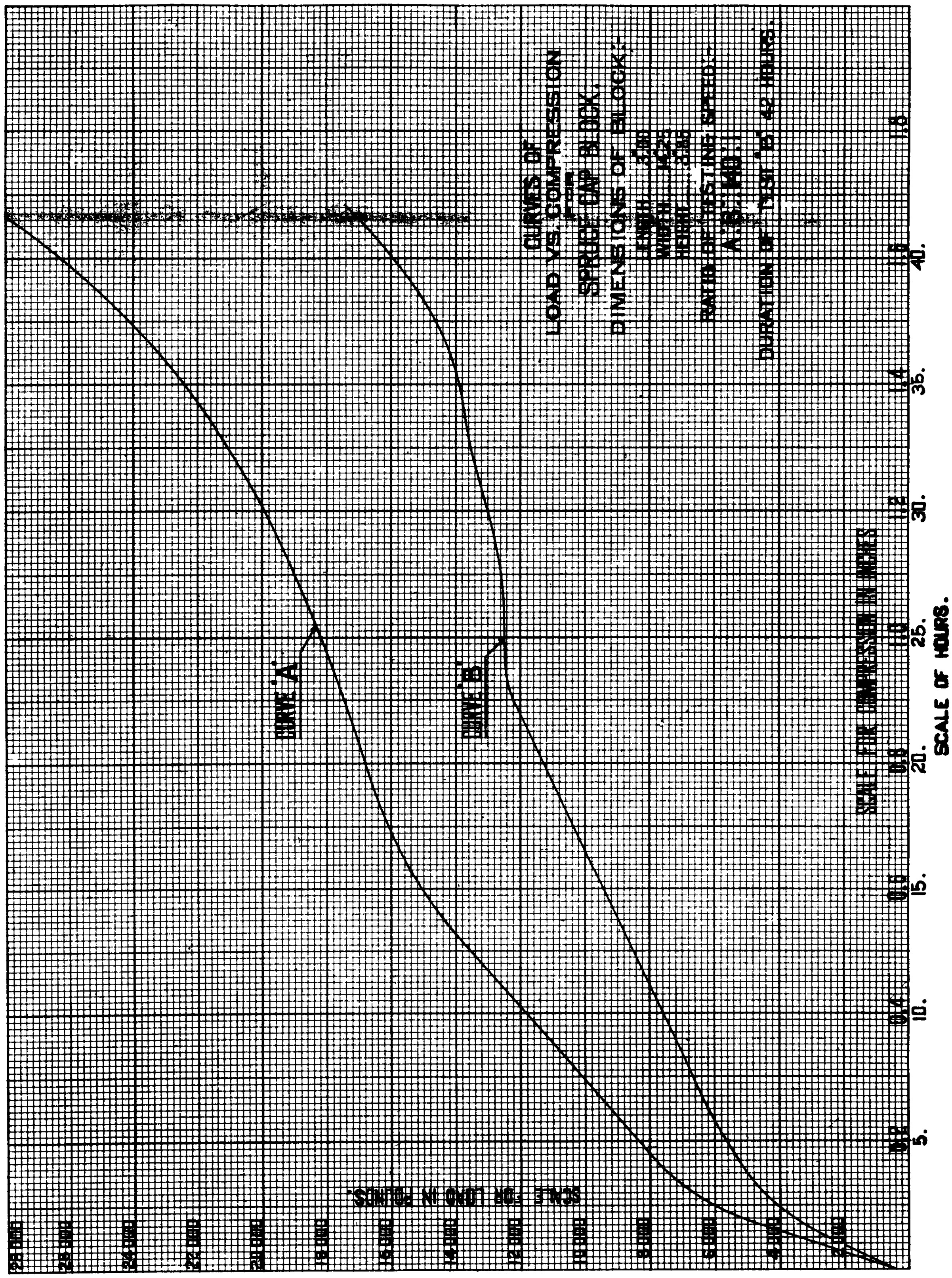

Time-Deflection Curves
for
Keel Blocks under a
load of 400000 lb.
"B" test No. 4
"A" test No. 3
26
24
22
20
18
16
14
12
10
8
6
4
2
0
Time hours
0.1"
Load-Deflection Curves
for
Keel Blocks
"B" test No. 4
"A" test No. 3
"C" test No. 2
"B" test No. 1
Deflection at mid height
0.1"
600
500
400
300
200
100
0
Load lb/in²

PLATE IX



Time-Strain Curves for Keel Blocks under a total load of 400,000 lb. (596 lb/in²)
t = Time-hours
d = shortening under a load of 596 lb/in²
0.005 in/in
A
B
d = 0.00688 t^0.316
d = 0.00497 t^0.226
0
2
4
6
8
10
12
14
16
18
20
22
24
26

PLATE X



CURVES OF
LOAD VS. COMPRESSION
FOR
SPRUCE CAP BLOCK.
DIMENSIONS OF BLOCK:-
LENGTH
WIDTH
HEIGHT
RATIO OF TESTING SPEED:-
DURATION OF TEST "B" 42 HOURS.
CURVE "A"
CURVE "B"
SCALE FOR LOAD IN POUNDS.
SCALE FOR COMPRESSION IN INCHES
SCALE OF HOURS.
28,000
26,000
24,000
22,000
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
5.
10.
15.
20.
25.
30.
35.
40.

PLATE XI

DIAGRAMS ILLUSTRATING VARIOUS ASSUMPTIONS AS TO CONDITIONS OF LOADING AND DEFLECTION OF KEEL BLOCKS UNDER A SHIP

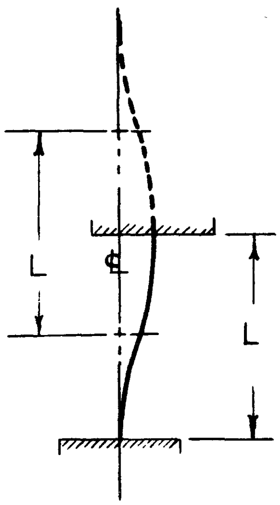


FIG.—1

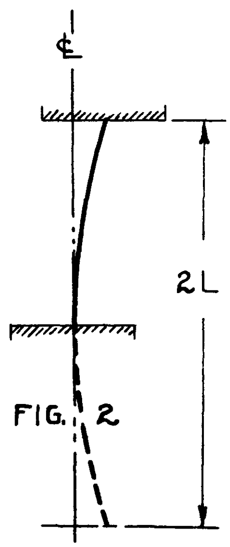


FIG.—2

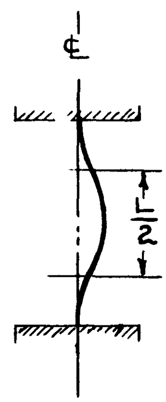


FIG.—3

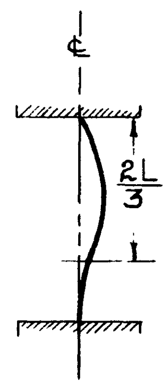


FIG.—4

TYPICAL KEEL BLOCKS UNDER U.S.S. SOUTH CAROLINA

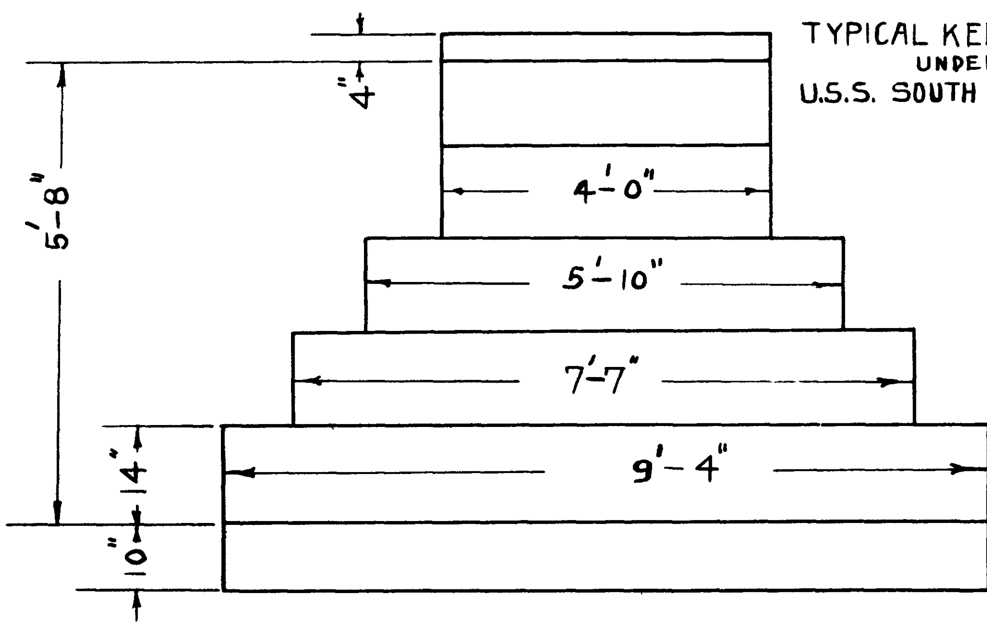
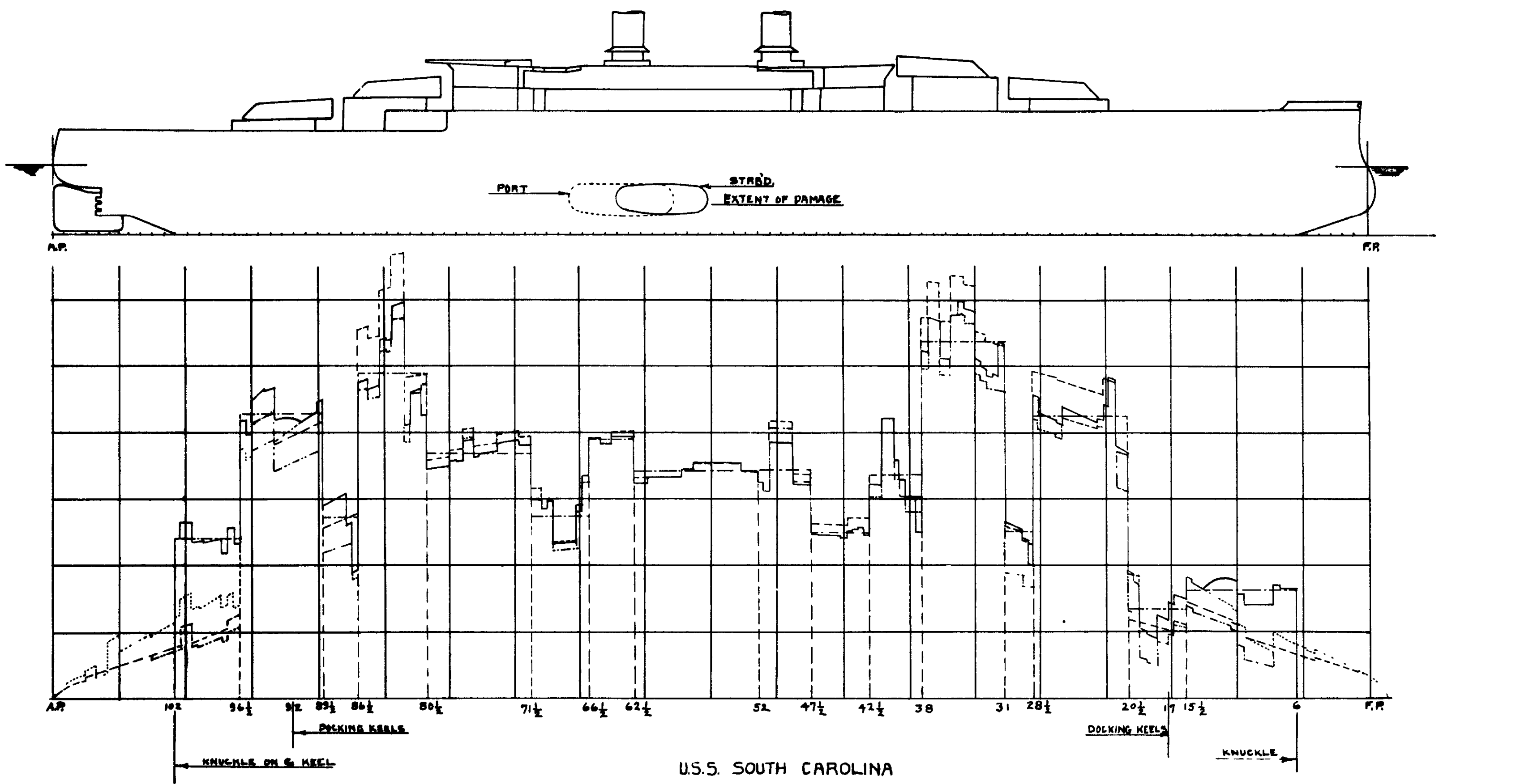


FIG.—5



U.S.S. SOUTH CAROLINA

WEIGHT CURVES FOR CONDITION AS DOCKED MAY 23, 1924.

PLATE XIII