

MOISTURE DISTRIBUTION IN WOODEN BEAMS

UNDER CONSTANT BENDING LOAD

by

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INTRODUCTION

Wood is a hygroscopic material which means that it can pick up or lose moisture according to the condition of the surrounding atmosphere. This moisture transfer continues until a balance is established between the moisture content of wood and the humidity of the surrounding conditions. The final moisture content attained by wood due to this effect as well as due to prevailing temperature and atmospheric pressure is commonly known as the equilibrium moisture content.

Moisture transfer will introduce two major problems in wood below the fiber saturation point: changes in variation of mechanical and physical properties, and dimensions. These changes with regard to moisture content are different in radial, tangential and longitudinal directions of wood since it is an orthotropic material.

The duration of moisture transfer below the fiber saturation point is governed by the laws of diffusion. This process is not a simple one since wood is a highly complex structure as previously reported by Moschler (33) and Hart (18).

In practical applications, according to Pearson (34), seasoning may produce an increase of 50% or more in the inherent bending strength of high grade timber. Variations in strength properties in relation to moisture content changes follow an exponential function (40).

In the past when wood was used in structures, builders, and designers did not give full consideration to this important phenomenon of the moisture dependence of wood properties. At present in the Harlem District of New York where buildings are under rehabilitation, some 4-1/2" x 12" x 26' supporting beams were found to have deflected as much as 10" during the past 70 years, with some of the deflection resulting from the unequal settlement of supports. (Compliment of Smith (36) Figure 1).

Recently it has been noticed by Barkas (5), Bello (7), and Davidson (13) that not only the condition of the surrounding atmosphere but also internal and external forces have influence on the moisture content of wood.

Internal forces may be introduced by drying, growth condition, uneven dimensional changes, external forces or by their combinations. This means that a stressed and a stress-free wood will have different equilibrium moisture contents under identical surrounding condition.

Preliminary investigations illustrated in Figure 2 were conducted at Virginia Polytechnic Institute by the author. They resulted in the same conclusion as those reported by the investigators to whom reference is made (Figure 2).

The scope of this study has been developed on the basis of the previous observations and following theories. Based on Barkas' results (5) one can say that in a non-uniform stress field such as that in bending, where tensile and compressive stresses exist, each stress

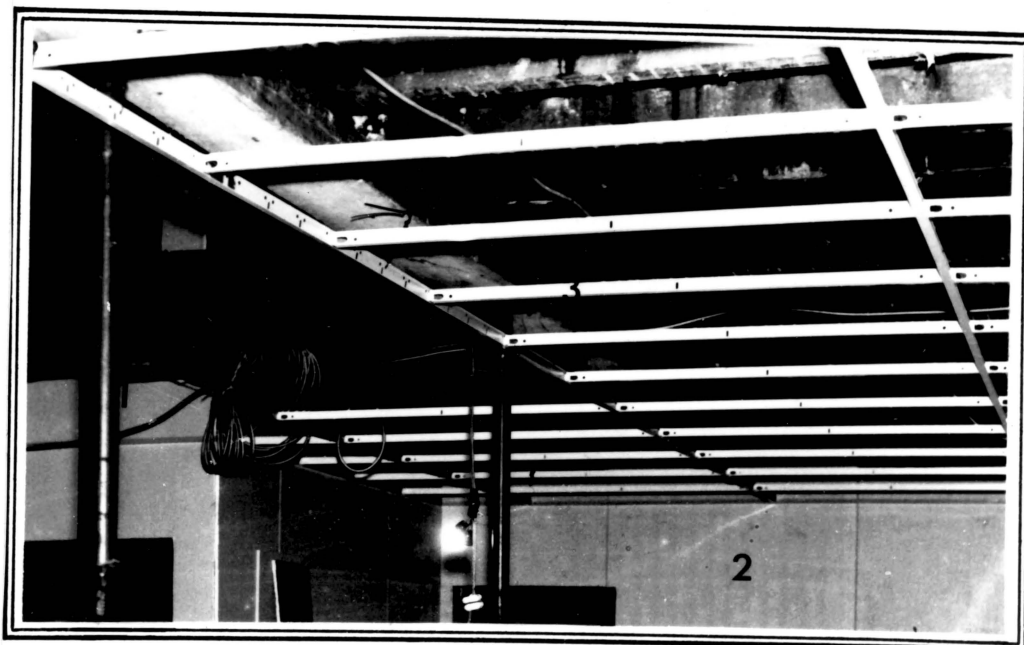
Figure 1. Building under rehabilitation in New York Harlem, (635 East 5th Street) photographed by W. R. Smith.

- a. The floor level is deflected five inches in this room.**

- b. General view of shaft for prefabricated bathroom-kitchen core units (1), vinyl-covered gypsum walls (2) and frame work for suspended gypsum ceilings (3). Note the bent beams.**



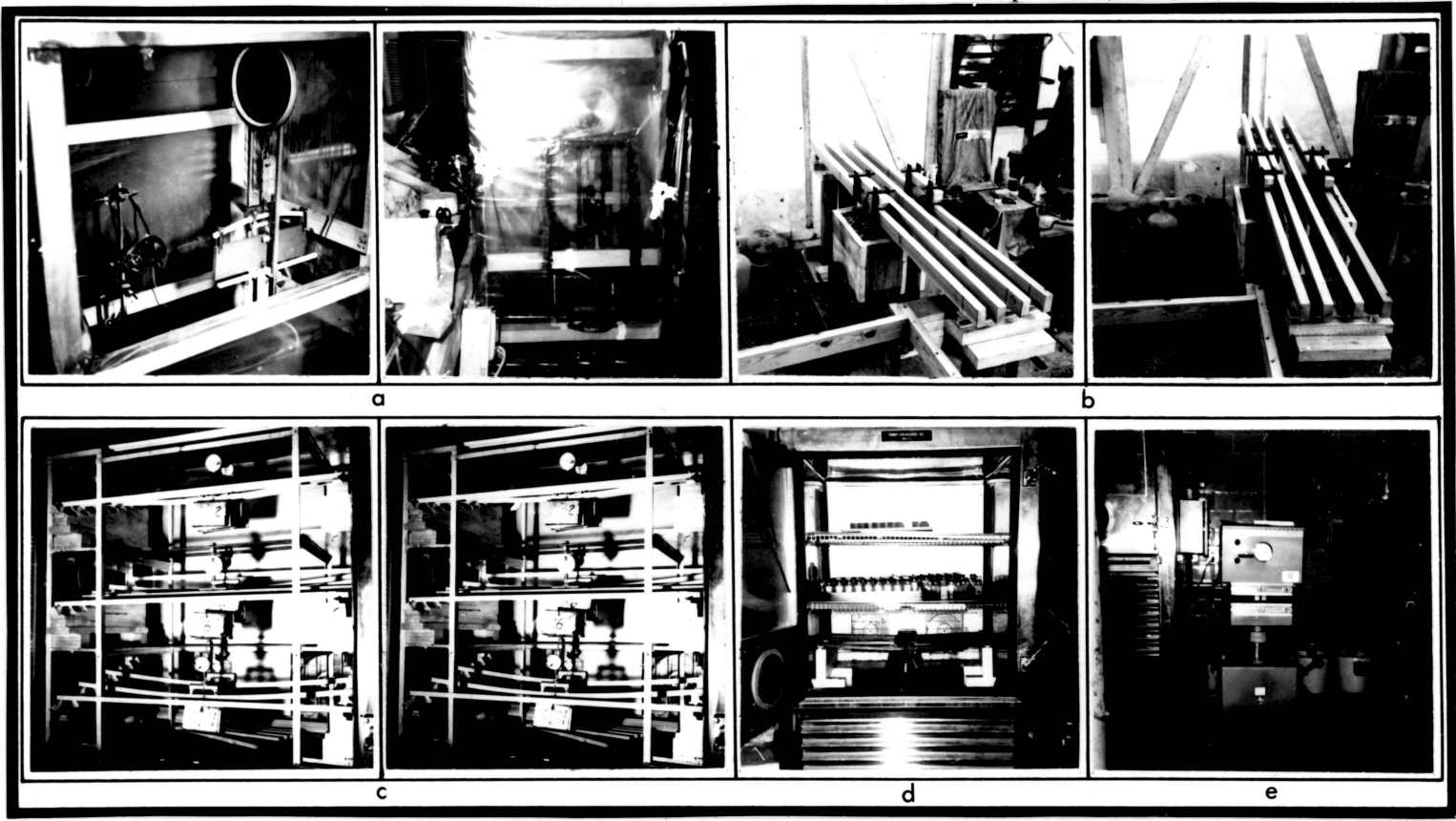
a



b

Figure 2. Preliminary experiments on the effect of moisture content change due to stress application in wood.

- a. Relaxation test with small beams in adsorption.
- b. Creep bending test with large beams in desorption.
- c. Creep bending test with small beams in constant humidity condition.
- d. Directional effect on moisture content distribution using small beams under bending in constant relative humidity conditions.
- e. Compression test in desorption.



a

b

a

d

e

level for both kinds of stresses should influence the moisture content of wood in a different way.

The objectives of this investigation can be stated as follows:

(1) To provide information on moisture distribution in wooden beams under constant load of various levels during moisture transfer condition; (2) To show whether or not different types of stresses influence the moisture content level during moisture transfer condition; (3) To study the creep behavior of wooden beams during adsorption and desorption of moisture; (4) To analyze and explain the relationship between stress level and moisture content in flexed beams.

REVIEW OF LITERATURE

The literature survey hereafter will include all the important previous investigations known to the writer which were considered to be in relation to the objectives of this study. These investigations will be discussed in two separate chapters according to their main subject matter.

1/ Creep Studies in Wood in Relation to Moisture Content Changes

If under any condition in any material deformation takes place while load is held constant this deformation is known as creep. It could be defined as the time dependent part of strain resulting from stress.

The creep phenomenon has been noticed for quite some time but little work has been done in this field until recent years. According to Clauser (10), the first few studies were minor in scope and were conducted under little or no control of atmospheric condition.

In 1947 Wood (42) reported on the results of the first creep study conducted by the U. S. Forest Products Laboratory in Madison, Wisconsin. This report includes a quantitative relationship between deformation, stress, and duration of load and the safe loading capacity of structural timbers. In 1951, as a follow-up, Wood (43) presented a mathematical expression for the relationship of bending strength

and duration of load. This empirical formula was found satisfactory and could be considered satisfactory for general use at constant relative humidity condition.

In Australia, work on the creep phenomenon had commenced in 1949. In 1951, Kingston and Armstrong (25) demonstrated that deflection of beams under load increased at a diminishing rate for at least one year. If, however, failure commenced during this period the deflection was found to continue at an increasing rate. In 1953, Higgins (20) reported a method for the determination of the relative effect of various factors on the plastic deformation of wood and plywood in compression.

During a study of the mechanical conditioning of high polymers, Grossman and Kingston (16) found that a comparison of creep and relaxation cannot furnish information on the existence of mechanical conditioning. Grossman suggested that an explanation of permanent creep can be found from the difference between a creep curve and the creep recovery curve provided high precision in measuring of creep is possible.

In Japan, creep investigations were conducted during 1956 to 1958. Sugiyama experimented with small beams of Japanese woods under long-time loading. His results were somewhat similar to those of Wood and of Kingston and Armstrong according to Caluser (10).

While studying strain behavior of wood subjected to repetitive stressing in tension parallel to grain, Kellogg (22) reported that

the creep-cycle number relationship was similar for the three species involved in his investigation. This relationship could be expressed by a logarithmic equation.

Glaser (10), in 1959, indicated that creep behavior up to the point of inflection on creep curve could be expressed satisfactorily by a relatively simple empirical equation which was somewhat similar to that of Kellogg's equation.

The interaction of wood and moisture is a problem which remains significant after construction. Bois (8) investigated the seasonal variation of moisture content of structural wood elements in homes. According to his results the largest changes occur during spring and fall, as can be expected.

Armstrong and Kingston (2), studied the effect of changes in moisture content on creep in wood, using small beams of different species. According to their results moisture content of wood markedly influenced creep while under load. The strains in extreme fibers were much greater on the compression face of beams than those on the tension face. Stress relaxation showed somewhat similar trends.

Armstrong and Christensen (1) reported that during prolonged flexural load application, the change in moisture content affected the rate and magnitude of deflection. Their results indicated that most of the deformation occurred within that period, during which moisture content changes took place. The magnitude of this deformation was found to be dependent mainly on the extent rather than on the rate

of moisture content change. The mechanisms involved in this phenomenon were not explained satisfactorily.

Kingston and Clarke (26, 27) reported that the relationship between creep deformation and stress deviated from linearity at stresses above approximately 40% of ultimate strength. With increasing temperature, both temporary and permanent creep were found to increase considerably. The effect of the rate of loading under stress or stress-strain curve was negligible. Authors also attempted to explain the molecular nature of temporary creep. According to them, molecular segments are involved in recoverable flow. This flow was thought to be small and may have occurred in the non-crystalline regions.

As reported by King (23) creep was found proportional to the logarithm of time for only the first 30 or 40 minutes. Creep occurred in all species investigated at the stress level amounting to 15% or less of short time strength. The initial strain creep and stress-level creep showed a two stage relationship.

Armstrong and Kingston (3) found that deformation of wood in bending and compression increased markedly during desorption of water in both single and repeated changes in moisture content. The tensile deformation decreased by a small amount or remained unchanged. During the first adsorption cycle of initially air-dry wood in bending and tension, the deformation increased, however, in all subsequent adsorption cycles the deformation decreased in bending and compression and increased slightly in tension. The rate of deformation after each cycle increased

gradually. The fractional deformation of wood in compression was greater than that in bending which in turn was greater than that in tension. Stresses due to moisture gradients did not appear to be responsible for the increased deformations occurring during changes in moisture content.

Christensen (9) used small beams under constant load to study the effect of changes in moisture content on the deformation of wood. Due to the exceptionally small size specimens used, test results were obtained rapidly because moisture diffusion and gradient were minimized. The results indicated similar relationship between change in moisture content and deformation as those reported by other Australian investigators.

During studies of creep, relaxation and failure of wood, Kingston (24) found that the time-dependent deformation was greatly influenced by changes of moisture content and by temperature. The creep deformation on the compression side of beams was found to be higher than that on the tension side. According to Kingston this may be caused by the fact that strength of wood in tension is higher than in compression. Creep deformations in compression, bending and tension parallel to grain were approximately the same under constant moisture content conditions. But when the moisture content conditions were varied, creep was found to be less in tension than in compression or in bending. Kingston indicated that there was no significant difference in creep behavior of wood of different species.

Davidson (12) reported on some results of the influence of temperature on creep in wood. Small increases in the slopes of the creep recovery curves were observed at temperatures up to 50° C. This change in the slopes was much larger for curves determined from tests performed at temperatures in the range of between 50° C to 60° C.

During investigations of nailed joints constructed of Australian woods, Mack (30, 31, 32) has found that creep in nailed joints after load application may be considerable. Higher load had produced larger total displacement. The fractional creep was thought to be linked with the nail withdrawal resistance.

Grossman and Kingston (17) studied the rheological behavior of wood in order to determine under what conditions Boltzmann's superposition principle may be applied. According to their results, the value of the products of empirical creep and relaxation functions as a criterion of linearity which was depending on the introduction of a lower limit of the function. The limiting stress of linear behavior was lower in green than in dry wood but it did not seem to be greatly affected by temperature. The individual tests were performed under various conditions in which the temperature and humidity kept constant.

Grossman (15) published a summary of the results of research on rheology of wood obtained by the Division of Forest Products of the Commonwealth Scientific and Industrial Research Organization in Australia. The content was discussed earlier by individual investigators.

Young and Hilbrand (44) studied the time-related flexural behavior of small douglas fir beams under prolonged loading. The time to failure was found to decrease as the stress level was increased, but it was independent of moisture content. The creep deformation and time relationship up to the inflection point could be represented by a relatively simple equation. This equation is identical with Clauser's (10).

Hearmon and Paton (19) conducted experiments similar to those by Christensen (9), Kingston and Armstrong (24). These experiments showed that creep deflection was dependent on applied load, moisture content and temperature. The large deflections observed during the tests did not produce significant changes in the modulus of elasticity.

Trussed rafter joints during moisture cycling have been studied by Wilkinson (41). His results showed that the deflection of bending specimens subjected to moisture cycling was much greater than those for uncycled specimens. In tension specimens the same phenomenon was observed. The final deformation again was greater for specimens which were subjected to moisture content cycling.

Recently the U. S. government and industry have begin to rehabilitate some of the slum areas in large cities. The actual reconstruction of a few buildings has been completed in the Harlem District of New York City. The structural wood members in these houses showed large time dependent deformation according to Smith (36). (Figure 1).

2/ Dependence of Sorption Equilibrium of Wood on Mechanical Stresses

In a clamping experiment on beech boards, Knight and Newall (28) noticed that the effects of clamping lowered the moisture contents of boards by a small amount. These differences seemed to be reversible as they showed a decreasing tendency with time.

Barkas (4, 5, 6) reported that creep could be considered an effect of plasticity but one must also make allowance for elastic creep. On the basis of a P, V (pressure, volume) diagram, one can conclude that wood will pick up less moisture while under restraint than when it is stress-free (Figure 3). This phenomenon also can be interpreted to mean that when stress is acting upon wood in a constant humidity condition, it will lose moisture to the surrounding atmosphere. The direction of the acting stress and the moisture content of wood have a definite bearing on this effect. Barkas also pointed out that the elastic constants are different for stresses of short duration and for sustained loads.

Treloar (38) has studied adsorption of water by hair, and its stress dependence. His experiment showed that the water content of horsehair in tension was increased by a small amount. This observation is in agreement with the thermodynamic theory of elastic gels.

Treloar's results indicated the opposite effect of those of White and Stam (38) who reported on similar experiments with human hair.

During a later experiment Treloar, (39) found that isotropic fibers under constant tensile stress for 25 minutes increased their

Figure 3. Pressure Volume (P, V) Diagram. (Adopted from Barkas (5))
The detailed explanation is included in the text. (pp.76).

moisture content considerably. In tests over longer periods, this increment diminished possibly due to ultra-structural orientation while under the influence of stress.

Kubat and Nyborg (29) experimented with restrained kraft paper, and found that moisture content increased by small amounts in both the cross and machine direction.

While experimenting with individual holocellulose pulp fibers under axial tensile stress in drying condition, Jentzen (21) found that fibers extended at the beginning of the test. However, deformation did not appear to be dependent on drying stresses. The stressed fibers showed superior mechanical properties and a higher degree of crystallite orientation, but crystallinity itself remained unaffected as compared to those of stress-free fibers. Jentzen also indicated that springwood fibers showed larger changes during these than summerwood fibers.

Recently Bello (7) conducted experiments to determine the magnitude of changes in the equilibrium moisture content of wood when allowed to take up moisture while being restrained from swelling by the application of compression acrossed the grains. Average differences due to restraint were found to range from 0.51% to 1.44%. These differences were increasing with increasing specific gravity. When the restraint was removed, the differences gradually disappeared indicating that this phenomenon is probably reversible. Other investigations also showed the reversibility of this phenomenon (28, 39).

According to Davidson (13) the application of mechanical stresses upon wood would create only small differences in moisture content, based on recent studies at Syracuse University.

MATERIAL AND METHODS

1/ Material

Beams $3/8'' \times 1/2'' \times 32''$ in dimensions were used in these investigations. They were prepared from yellow poplar (Liriodendron tulipifera L.). Logs were cut at the Virginia Polytechnic Institute Research Forest, and sawed into 2" planks at a local sawmill. The planks were checked and only those were selected for beam material whose grain direction and growth-rate were satisfactory and which were free of defects of any kind. Beams were rough sawed from the sound heart wood in the approximate dimension of $4/8'' \times 5/8'' \times 32''$. Then, the beams were inspected again to fulfill the requirements specified hereabove. Using an accurate planer the rough 32" beams were planed to their final dimensions: $3/8''$ radial \times $1/2''$ tangential. Then, they were lightly sanded using fine sandpaper to remove loose slivers. After having made all the beams required for the entire experiment, they were stored in a humidity chamber with the condition equivalent to approximately 11% equilibrium moisture content.

The beams were prepared for the performance of the experiments in the following way: First, they were appropriately labeled, then the points over which the load was to be applied and the position of supports were marked on the beams. The depth of the center one-inch

part of the span of each beam was marked into five equal sections to indicate the locations for moisture content determinations. These markings are shown in Figures 4 and 5.

2/ Experimental Design

During this investigation of the moisture distribution in small yellow poplar beams under constant bending load, four independent experiments were conducted: two in adsorption and two in desorption. The total duration of each experiment lasted approximately ten days.

The average initial and final moisture contents for four experiments are given in Table 1.

Table 1. Average initial and final moisture contents of the four experiments.

<u>Experiment</u>	<u>Initial Moisture Content in %</u>	<u>Final Moisture Content in %</u>
Adsorption 1	6-7	22-23
2	6-7	24-25
Desorption 1	17-18	6-7
2	22-23	6-7

For each experiment, beams were divided into three categories according to the constant load levels. Three replicate beams were taken from the humidity chamber at six time intervals during the test period. Table 2 represents the number of beams involved in an individual experiment.

Figure 4. An illustration of five sections cut from a beam, and their corresponding containers.

L - light load level
P - light load

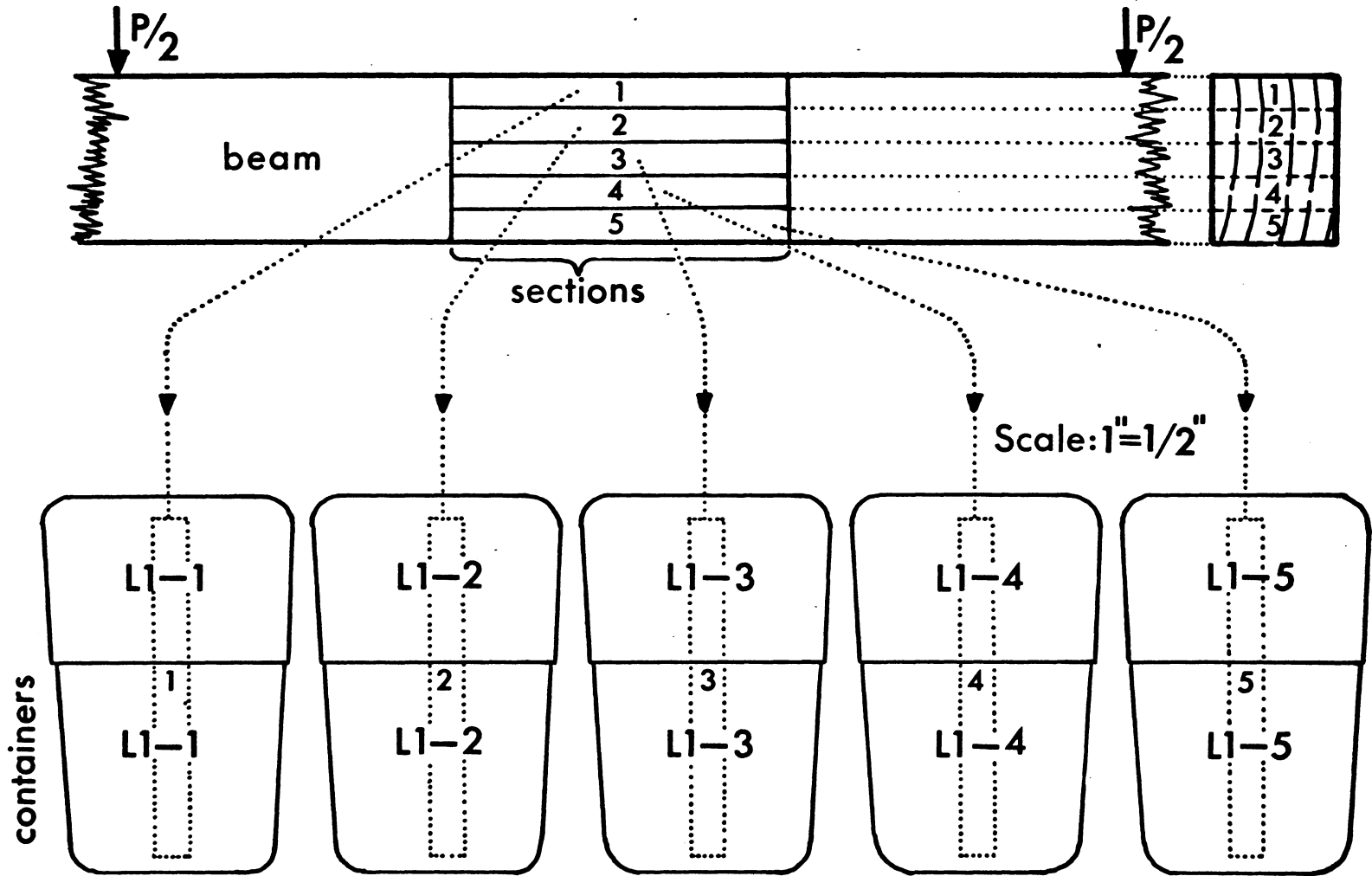
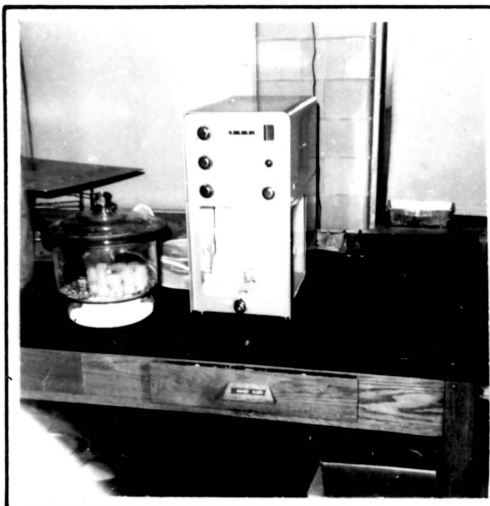
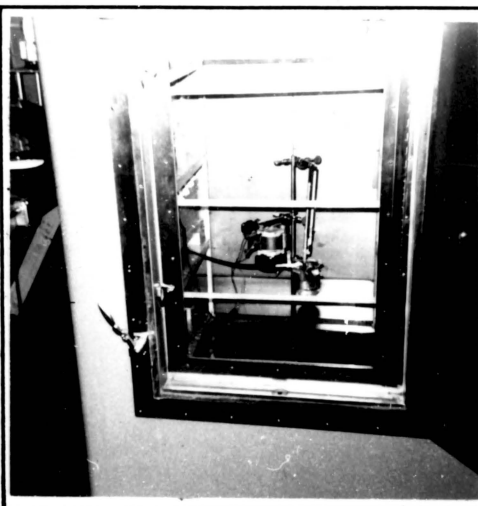


Figure 5. Equipments used during the investigations.

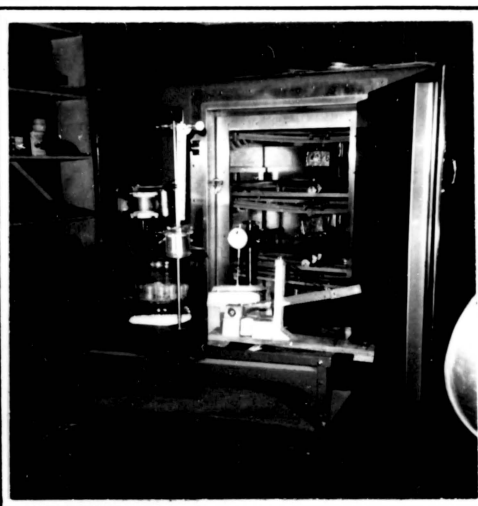
- a. Desiccator with containers and Ainsworth analytical balance.
- b. Dry-wet bulb thermometer set up for checking chamber condition.
- c. Partially loaded chamber, cutting device and dial indicator.
- d. A support level, loading, and deflection measuring devices.
- e. Sections with containers in oven.
- f. Rubber gloves, cutting device, desiccator and dial indicator.



a



b



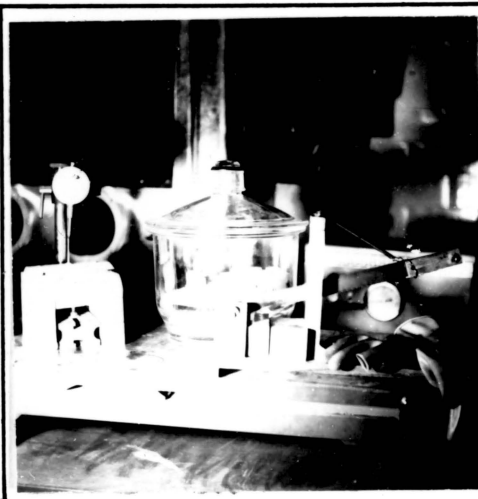
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d



e



f

Table 2. Number of beams by categories for each experiment.

Category	Take Out No.						Total
	1	2	3	4	5	6	
Control (no Load)	3	3	3	3	3	3	18
Loaded (light-2.205 lbs.)	3	3	3	3	3	3	18
Loaded (heavy-4.410 lbs.)	3	3	3	3	3	3	18
Total	9	9	9	9	9	9	54

The total number of beams used in each experiment was 54. In addition, 3 beams were used to determine the exact initial moisture content for each experiment. This amounted to 57 beams per experiment, and the total of 228 beams for the entire study.

The time intervals between take outs were uneven as can be seen in Table 3. Since most of the moisture transfer took place in the early part of experiments, the time intervals were selected with these in mind.

Table 3. Time elapsed between take outs.

Take Out No.	Time elapsed in hours
1	4
2	20
3	50
4	80
5	150
6	240

This experimental set up conforms to a factorial statistical design as shown in Table 4.

Table 4. Experimental design for the study of moisture distribution in yellow poplar beams under constant load during moisture transfer conditions.

Source	Levels
Sorption condition	2
Load level	3
Take out interval	6
Vertical position in beams	5
Sample replicate	3
Experiment replicate	2
Total	1080

3/ Condition Control and Test Set-up

An Aminco humidity chamber was prepared for the performance of the bending tests. Shelves were installed along the two sides of the chamber leaving adequate space for free movement of water vapor at the center portion and providing sufficient room for the deflection measuring devices. The shelves provided four support levels on which the actual supports were placed. The supports were of simple type, that is a combination of wedge and roller. These facilities were made of wood and plywood covered with aluminum paint to reduce dimensional changes due to moisture transfer. The supports were constructed in such a way that they provided unobstructed view of each beam during each experiment.

The supports are shown in Figure 6, while deflection measuring device is illustrated in Figure 6g. The Aminco unit is shown in Figure 7, as it was made ready for the performance of the bending tests.

4/ Load Levels and Loading Devices

Constant load was applied at two points to avoid shear stresses at the center portion of the beams where the moisture distribution was to be measured. This loading arrangement also eliminated direct compressive stresses perpendicular to the span at midpoint of the beams. The distance between the load application points was three inches and the load was distributed evenly in such a way that half of the total load was acting at each application point spaced 13-1/2" from the supports. The load was applied on the radial face of the beams, as shown in Figure 4. This loading system resulted in sufficiently large stresses at the center portion of the beams where the moisture distribution was to be measured.

Two load levels were designed, that is, a light-2.205 lb. level and a heavy-4.410 lbs. level. Both of the levels were selected below the elastic limits of yellow poplar to ensure that no failure occur during the experiments. The necessary calculations for the selection of these load levels, their numerical values and relation to the elastic limits in wet and dry conditions are given in Figures 8 and 9.

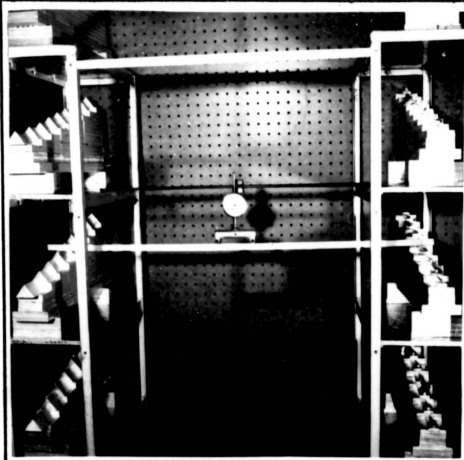
The loading device was designed and built, so that it would meet all the specified requirements. For each experiment there were 18

Figure 6. Shelves and actual supports in details.

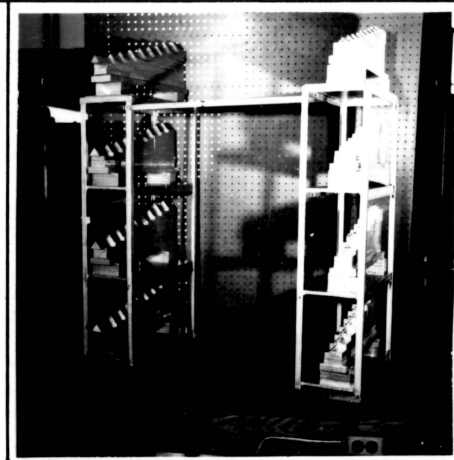
- a. Complete supporting unit.**
- b. Complete supporting unit with deflection measuring device.**
- c, d. Side views of complete supporting unit.**
- e, f. Details on the nature of the supports.**



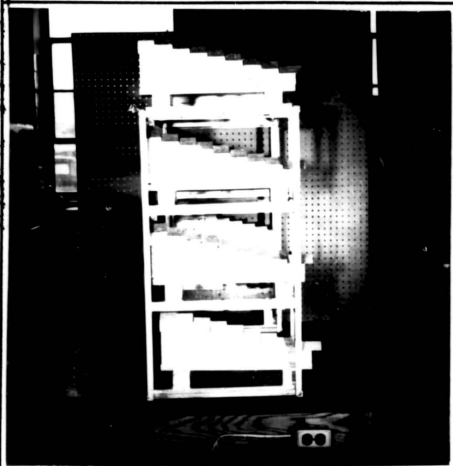
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b



a



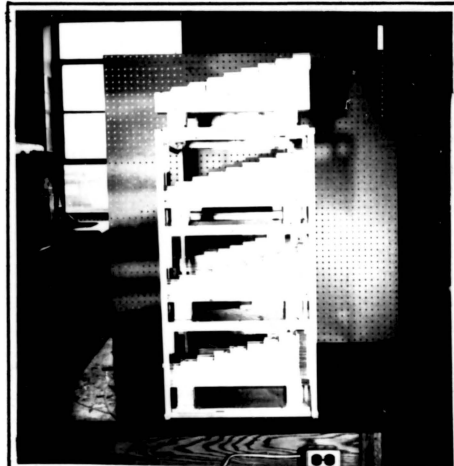
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e



d

Figure 6g. Deflection measuring device.

- 1 - Ames dial gage
- 2 - Hot-rol steel plate
- 3 - Support level
- 4 - Knot
- 5 - Washer
- 6 - Treaded rod

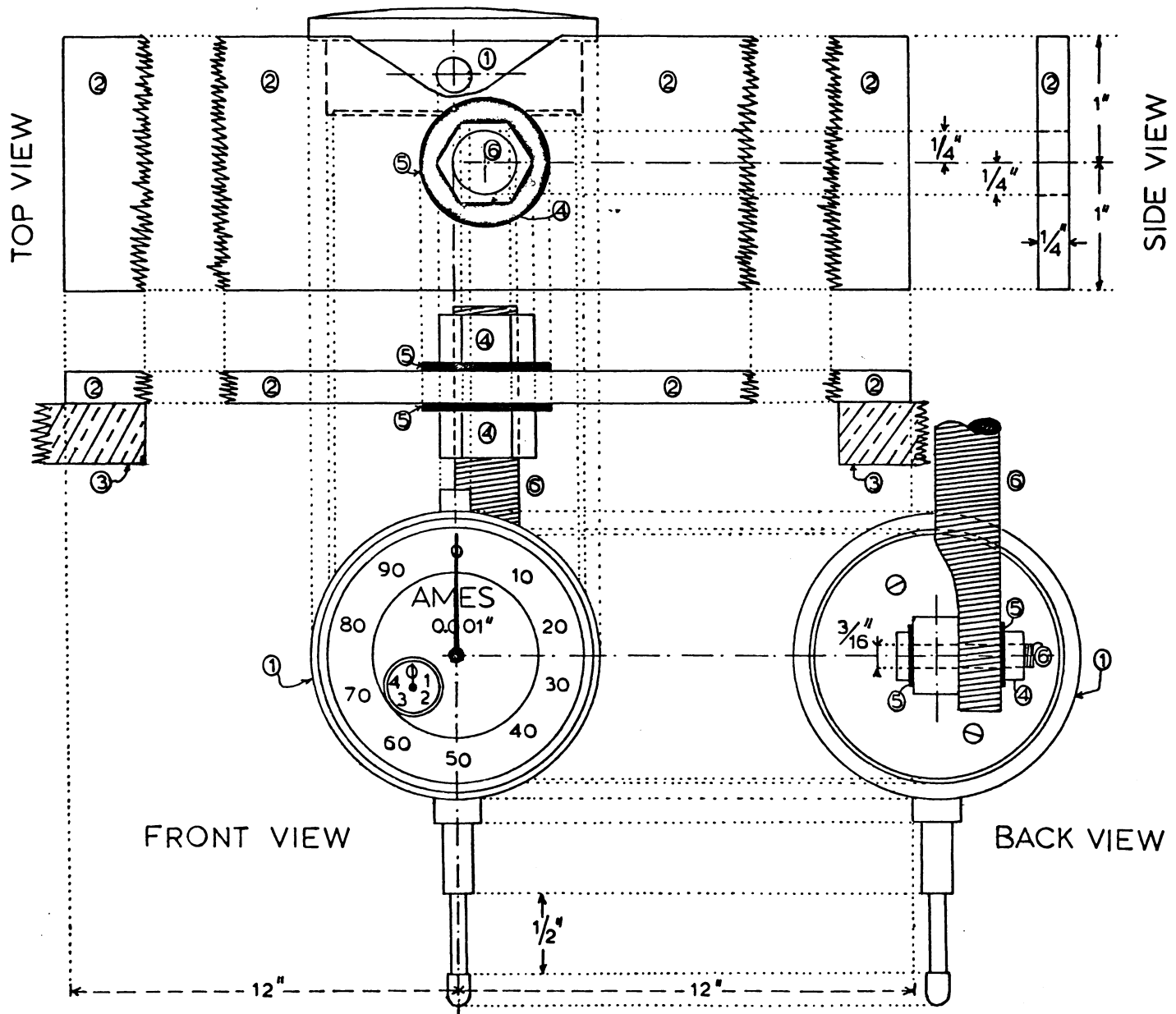
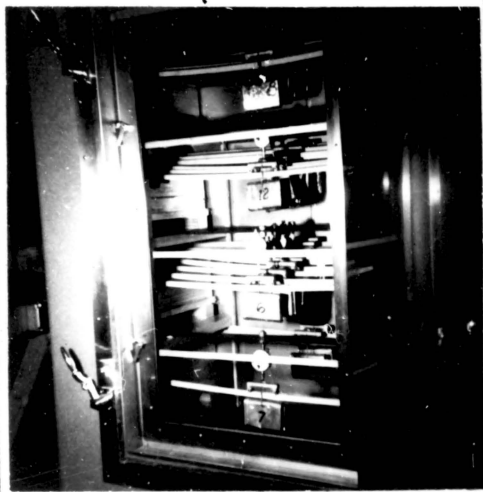


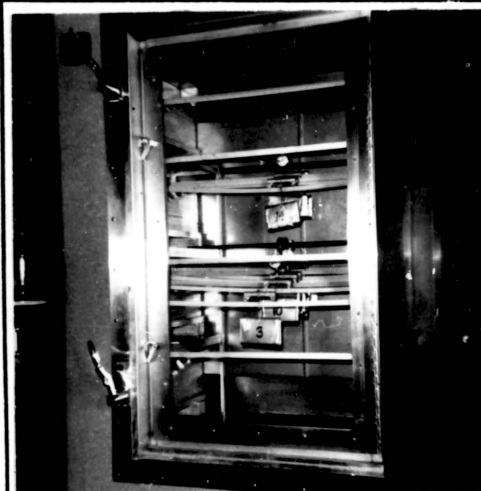
Figure 7. Aminco humidity chamber and beams during bending experiment.

a. Chamber with full load.

b. Chamber with partial load.



a



b

Figure 8. Acting forces and stress conditions during the experiments.

P, P' acting forces

R_1', R_2', R_1, R_2 reaction forces

S_m, S_m' maximum bending stresses

H_m, H_m' maximum horizontal shear stresses.

(prime stands for heavy load level, while no prime for light load level.)

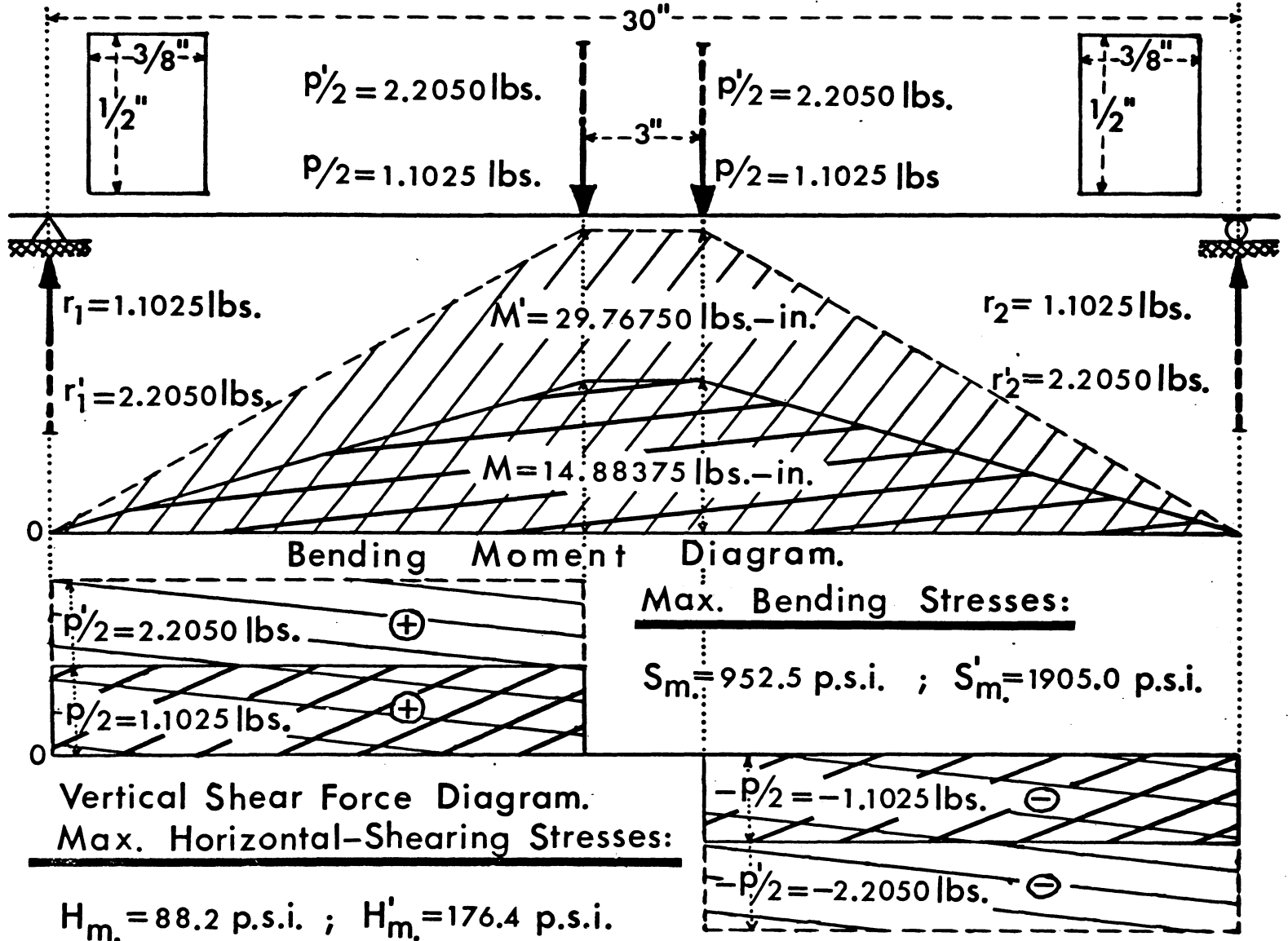


Figure 9. Position of load levels in the elastic range.

E_d Modulus of Elasticity in dry condition (p.s.i.)

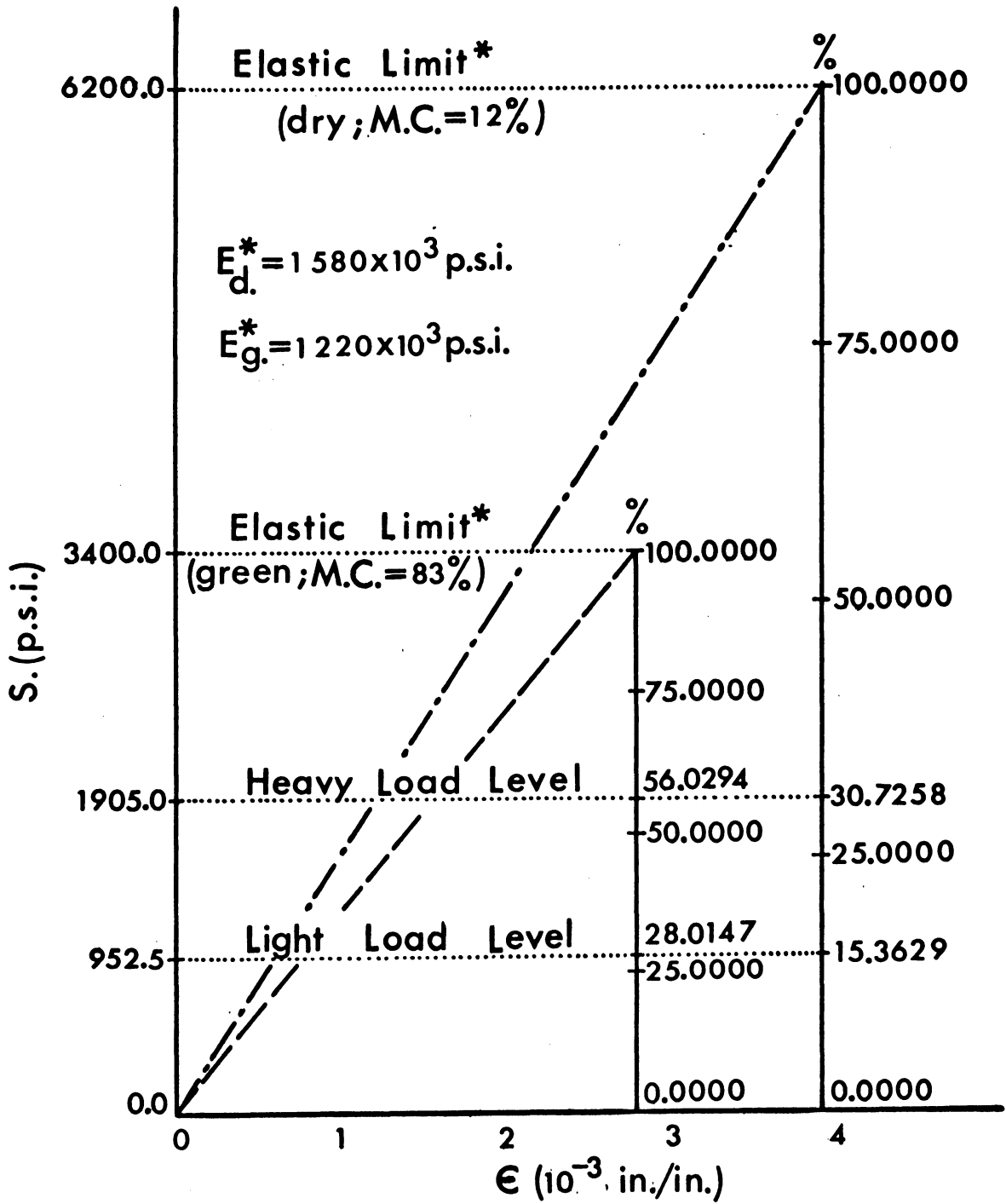
E_g Modulus of Elasticity in green condition (p.s.i.)

S Bending stress (p.s.i.)

ϵ Unit strain (in./in.)

M.C. Moisture content (%)

*** Source of data Wood Handbook (38).**



beams under load at each load level. Three of these beams were removed for each take-out for moisture distribution determinations.

The position of loading and the acting forces are also illustrated in Figure 8. The loading system and devices were essentially the same for all the four experiments and they are shown in details in Figure 10.

5/ Deflection Measurements

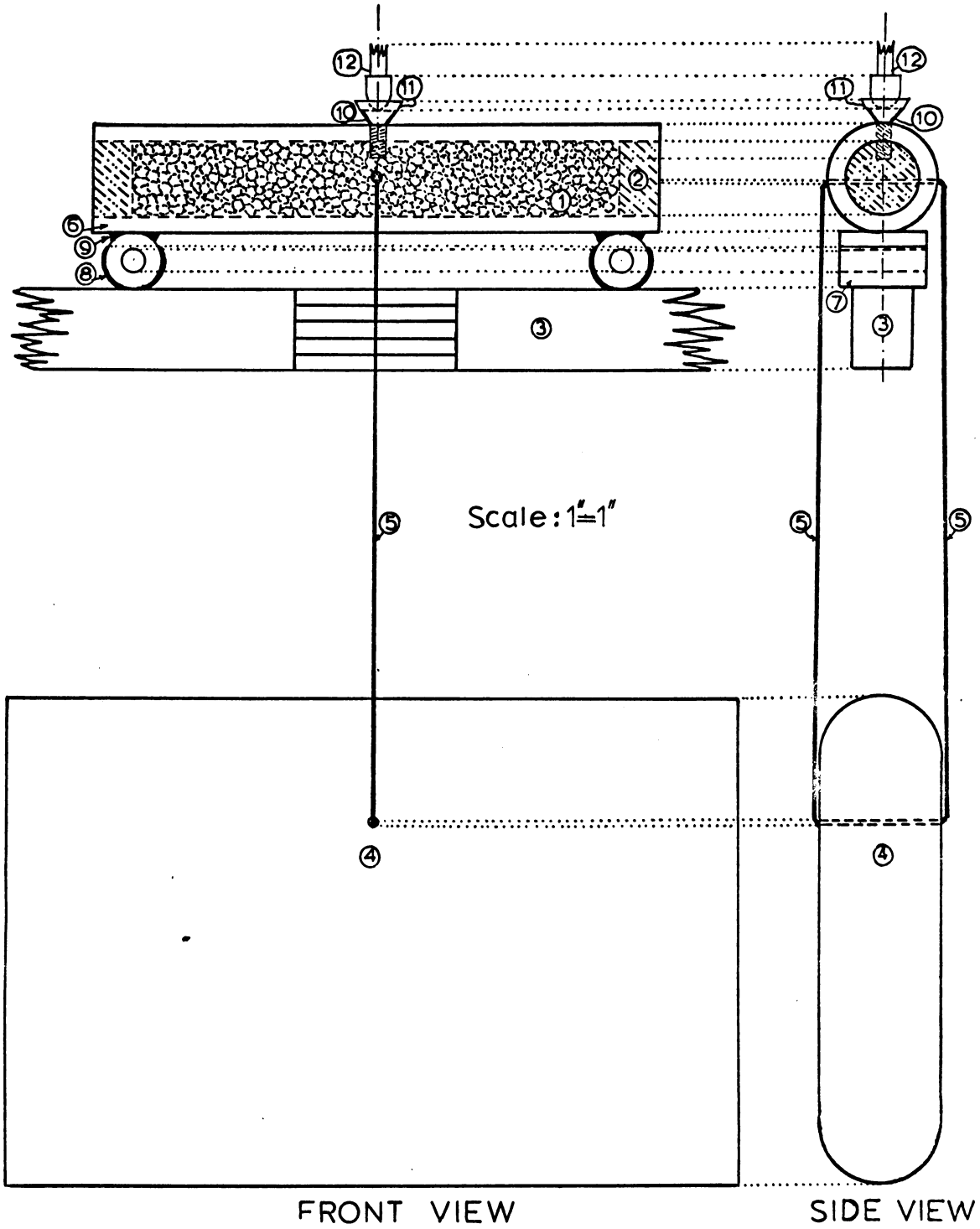
For the deflection measurements Ames dial gages with an accuracy of 0.001" were used in each experiment. Gages were used with six beams at each load level. At each take out for each load level three beams were removed from the chamber. For one of these beams the residual deflection was measured. Since this information was considered of secondary nature, the residual deflection of the other two beams was not observed.

Since the top shelf level of the supporting unit did not have any space for deflection measuring instruments, some of the control beams were placed on it, while beams with mounted gages were placed on the lower three shelf levels. (Figures 6 and 7).

Gages and loading devices were prepared ahead of time and tested prior to each experiment, to ensure their proper continuous working condition. They were identified with numbers for the convenience of recording creep deflections.

Figure 10. Loading device.

- 1 lead shots
- 2 rubber stopper
- 3 beam
- 4 lead block or container filled with lead shots
- 5 copper wire
- 6 steel pipe
- 7 steel pipe
- 8 rubber cover against stress concentration
- 9 spot-welding
- 10 screw
- 11 shield cup
- 12 dial gage



Average deflection was measured on center of steel pipe connected to the application points as shown in Figure 10. Initial creep deflection readings were taken at the beginning of the experiment ($t=0$) on each loaded beam. Then, measurements were taken at increasing time intervals as the experiment proceeded. In the first 24 hours, deflections were recorded frequently, since most of the total deflection occurred during this period. While taking these readings, adequacy of the test data to construct smooth creep-time curves was kept in mind.

The deflection measuring device and its location in the supporting system is shown in Figures 6 and 6g, while the loaded humidity chamber with beams is illustrated in Figure 7. The later figure also shows how the beams were loaded and how their deflection was measured during the experiment.

6/ Determination of Moisture Distribution

The main purpose of this investigation was to determine the moisture distribution at the center portion of the beams under sustained loading in moisture transfer conditions. To achieve this, the center 1" to 1-1/4" portion of the beams were split through four horizontal planes into five approximately even sections with the dimensions of 1/10" x 3/8" (1" to 1-1/4"). The average oven-dry weight of such a section was approximately one half gram.

There were two moisture transfer conditions: Adsorption and desorption, with each of them represented by two independent experiments of 10-day duration.

During the adsorption experiments beams were increasing their moisture contents from approximately 6% to 24%, under the following chamber settings: dry-bulb temperature 80° F, wet-bulb temperature 79° F and relative humidity 96%. During the desorption experiments, beams were decreasing their moisture contents from approximately 24% to 6% under the following chamber settings: dry-bulb temperature 80° F, wet-bulb temperature 60° F and relative humidity 29%.

The initial moisture content of the test material desired was obtained by preconditioning the beams for 4 to 5 days under one of the conditions specified above. The initial and final moisture contents of the four experiments were different because of a slight preconditioning error.

At the beginning of each experiment, three beams were sampled for initial moisture distribution. Then, three beams at each of three load levels were taken out of the humidity chamber at six different time intervals to determine transitional and/or final moisture distributions.

For the determination of moisture distribution the following procedure was used during all four experiments. Beams were removed from the humidity chamber individually and their premarked center portion was cut out with a handsaw. (Figure 4). These small blocks

(3/8" x 1/2" x 1" to 1-1/4") were split into five sections with a special single blade lever-action cutting device (Figure 5c,f). As soon as the five sections were cut, they were placed into premarked plastic containers (Figure 11). The plastic containers were identified according to the position of sections and the load levels that were acting on the beams. (Figure 4). This was necessary to eliminate recording errors. The use of these plastic containers was shown during the preliminary studies to improve precision in moisture content determinations. Prior to their use, the containers were dried under 105° C for one hour and were allowed to cool in a desiccator for approximately the same period of time.

As soon as the sections were placed on the appropriate containers, they were closed tight and the desiccator was closed. For convenience, three desiccators were used for the 45 containers at each take out (Figure 11).

Using an Ainsworth analytic balance, as shown in Figure 5a, the net wet weights of sections were determined using the following method:

$$N.W._w = G.W._w - C.W._i$$

Where: $N.W._w$ = net wet weight of section (gm)

$G.W._w$ = gross wet weight of section and container (gm)

$C.W._i$ = immediate container weight (gm)

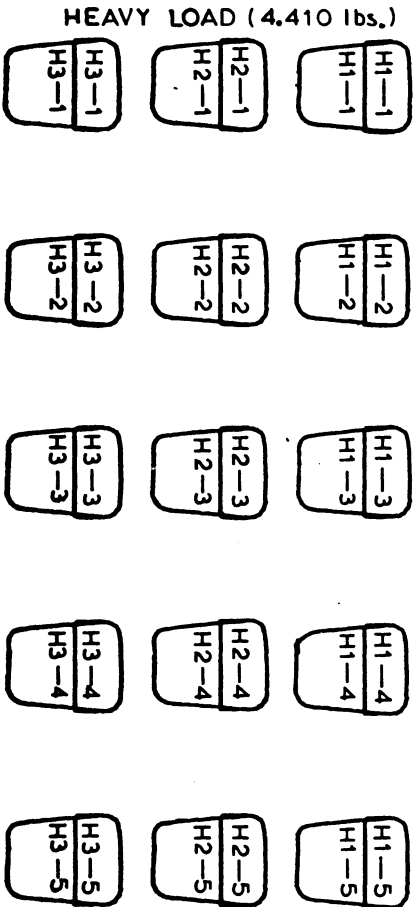
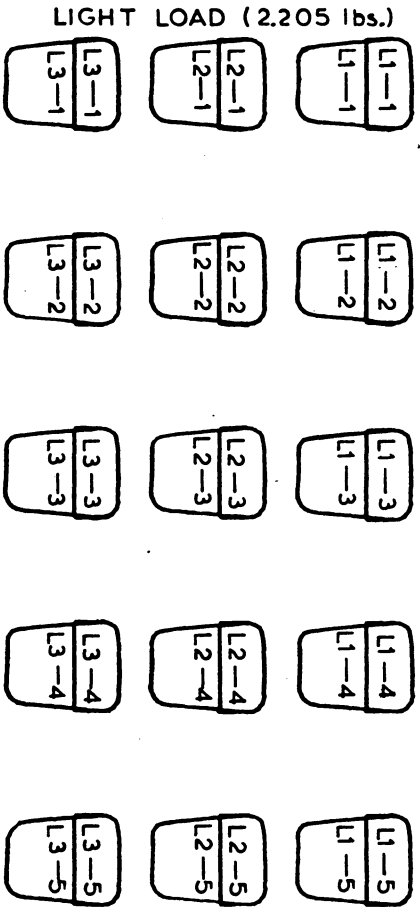
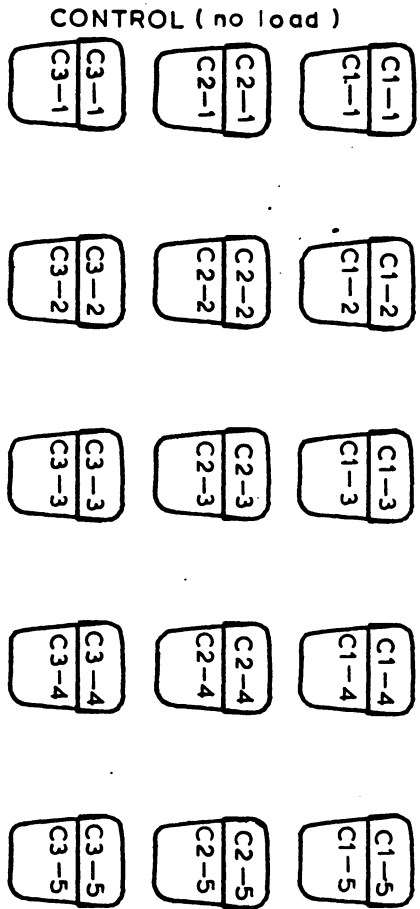
Figure 11. Identification of all containers.

C control

L light load level

H heavy load level

(first no. replication, second no. section)



After all the net wet weights had been obtained for a particular take out, the sections were dried in open containers in an oven at 105° C temperature for 20 to 24 hours. (Figure 5e). At the end of the drying period the sections in closed containers were placed back into desiccators and were allowed to cool for one hour. Then, their net dry weights were determined by using the analytical balance in the following way:

$$N.W._d = G.W._d - C.W._i$$

Where: $N.W._d$ = net dry weight of section (gm)

$G.W._d$ = gross dry weight of section and container (gm)

$C.W._i$ = immediate container weight (gm)

Knowing the net wet and dry weights of the sections, the positional moisture contents of the beams were calculated and recorded. The overall method of calculation can be summarized as follows:

$$M.C._p (\%) = \frac{(G.W._{wp} - C.W._{ip}) - (G.W._{dp} - C.W._{ip})}{(G.W._{dp} - C.W._{ip})} 100$$

Where: $MC._p$ (%) = position moisture content in percent

During handling of the sections and beams, rubber gloves were used to eliminate any moisture transfer through direct contact with fingers (Figure 5f).

The test procedure was essentially the same for all take outs with all load levels in all four experiments including initial moisture distribution determination.

RESULTS AND DISCUSSIONS

The experimental data collected in this investigation are presented in tabulated form. Positional moisture content data for the four independent experiments with regard to duration of load and load level are given in Tables 5 and 6. Creep deflection measurements as related to load duration for the various load levels are given in Tables 7 and 8.

1/ Grouping of Experimental Data for Analyses

Statistical analyses were made for evaluation of the test data. Since there were two adsorption and two desorption experiments in the investigation, it occurred that the two experiments in each moisture transfer condition might be regarded as replicates.

The results of the analyses of variance indicated that the above hypothesis was not appropriate because of large differences in either initial and final moisture content of the specimens for the individual experiments. Table 9 gives the detailed results of the analyses of variance. On the basis of this analyses it is evident that the experiments were significantly different from each other. Test specimens in the two adsorption experiments had different final moisture content, while the specimens in the desorption experiments had different initial moisture content. Numerically the difference for the desorption experiments was approximately 5 to 6% and for

Table 5. Distribution of moisture content in the two adsorption experiments.

		ADSORPTION EXPERIMENT NO. 1									ADSORPTION EXPERIMENT NO. 2									Moisture Content (%)
Take Out	Section	Controls (No Load)			Loaded (2.205 lbs.)			Loaded (4.410 lbs.)			Controls (No Load)			Loaded (2.205 lbs.)			Loaded (4.410 lbs.)			
		Replicate No.									Replicate No.									
No.	No.	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	
0	1	6.51	6.60	6.48	-	-	-	-	-	-	6.17	6.34	6.26	-	-	-	-	-	-	
	2	6.57	6.75	6.13	-	-	-	-	-	-	6.30	6.11	6.06	-	-	-	-	-	-	
	3	6.95	6.51	6.79	-	-	-	-	-	-	6.53	6.34	6.36	-	-	-	-	-	-	
	4	6.57	6.75	6.13	-	-	-	-	-	-	6.30	6.11	6.06	-	-	-	-	-	-	
	5	6.51	6.60	6.48	-	-	-	-	-	-	6.17	6.34	6.26	-	-	-	-	-	-	
1	1	12.50	13.38	13.04	12.48	13.26	11.80	11.99	12.44	11.72	11.47	11.85	11.72	11.66	12.21	13.63	12.67	12.24	12.21	
	2	10.03	10.44	10.28	9.87	9.83	10.04	9.50	10.07	9.45	9.48	9.52	10.31	9.63	10.02	11.25	10.15	9.88	9.90	
	3	9.79	10.41	9.65	10.02	9.42	10.28	9.42	9.77	9.23	9.47	9.02	9.71	9.57	9.40	10.77	10.16	9.39	9.03	
	4	10.03	10.44	10.28	10.19	9.93	10.17	9.54	10.01	9.14	9.48	9.52	10.31	9.65	9.86	11.52	9.94	10.23	9.88	
	5	12.50	13.38	13.04	13.30	13.50	12.95	13.12	13.16	11.65	11.47	11.85	11.72	12.64	12.56	14.79	12.61	13.94	12.22	
2	1	17.32	17.06	17.20	17.19	17.12	18.89	17.25	17.99	17.40	16.98	16.36	16.18	17.04	15.69	18.98	18.45	17.72	17.08	
	2	16.57	15.40	15.91	16.46	16.22	17.59	16.20	17.16	16.13	15.99	15.55	14.96	15.78	15.65	18.04	16.96	16.51	15.91	
	3	15.88	15.06	15.17	15.80	16.01	16.57	15.81	16.01	14.92	15.70	15.13	14.05	14.72	14.42	16.93	16.27	16.17	14.93	
	4	16.57	15.40	15.91	16.04	15.67	17.52	16.63	16.22	16.16	15.99	15.55	14.96	15.82	14.81	17.32	16.48	17.16	15.76	
	5	17.32	17.06	17.20	17.53	17.94	19.03	18.55	17.98	17.63	16.98	16.36	16.18	17.47	16.75	19.19	18.92	18.48	17.16	
3	1	22.03	21.48	22.57	21.41	20.97	21.83	22.06	21.25	20.96	20.72	21.39	20.85	19.03	19.26	21.00	20.98	20.18	21.04	
	2	22.05	21.36	21.49	20.61	21.36	22.78	20.97	21.00	21.48	20.81	21.25	21.14	20.26	19.41	21.65	20.72	20.21	20.57	
	3	21.86	21.37	21.86	20.76	20.99	22.64	20.22	20.73	20.94	20.53	21.52	20.51	19.94	19.12	21.58	20.29	20.08	19.82	
	4	22.05	21.36	21.49	21.05	20.94	23.00	20.74	21.56	21.62	20.81	21.25	21.14	20.02	19.35	21.92	19.78	20.39	20.33	
	5	22.03	21.48	22.57	21.32	21.08	22.60	21.39	22.09	22.09	20.72	21.39	20.85	20.64	20.43	21.71	21.13	20.74	21.53	
4	1	22.00	21.94	22.02	21.93	21.16	22.39	22.04	22.48	21.93	23.33	23.60	23.78	23.06	22.22	24.29	23.33	23.15	23.73	
	2	22.15	22.07	22.48	22.88	22.07	23.15	22.64	22.41	22.94	23.25	23.60	23.89	22.62	23.23	24.99	23.13	23.73	23.81	
	3	22.10	21.78	22.36	22.23	21.99	23.03	22.73	22.39	21.50	23.09	23.79	23.17	23.04	23.50	24.79	23.90	24.45	22.93	
	4	22.15	22.07	22.48	22.48	21.80	23.21	22.28	23.24	22.46	23.25	23.60	23.89	22.70	23.53	24.74	23.90	24.26	23.97	
	5	22.00	21.94	22.02	22.65	21.86	22.64	23.03	23.08	21.51	23.33	23.60	23.78	23.72	23.41	24.61	24.45	24.78	24.28	
5	1	22.21	22.23	21.74	21.91	20.72	21.62	22.55	21.28	22.38	23.92	23.82	23.11	23.58	23.35	22.22	22.81	22.70	21.99	
	2	22.77	22.75	22.49	21.80	22.47	22.68	22.74	22.44	23.69	25.12	24.55	23.53	24.44	23.80	24.29	24.01	23.35	23.75	
	3	23.03	23.31	22.37	21.79	22.76	22.84	22.42	22.85	23.39	25.19	24.38	23.42	24.49	23.90	24.01	23.94	23.73	24.04	
	4	22.77	22.75	22.49	22.38	21.62	23.13	22.39	23.77	23.86	25.12	24.55	23.53	23.62	24.62	24.36	24.36	24.37	24.11	
	5	22.21	22.23	21.74	22.10	22.49	22.35	22.36	23.41	23.20	23.92	23.82	23.11	23.86	23.69	23.64	23.38	23.58	23.26	
6	1	22.22	22.65	22.47	20.84	21.66	22.11	22.18	22.01	21.37	24.38	25.02	24.92	23.61	24.07	22.67	24.25	21.95	22.64	
	2	22.69	22.53	23.20	22.83	22.64	22.76	22.59	24.89	22.99	25.30	25.26	24.97	24.47	25.49	24.07	25.17	23.22	24.49	
	3	23.00	23.13	23.22	22.24	22.96	22.68	22.23	22.34	22.51	24.94	25.32	25.11	24.24	25.43	24.68	24.91	23.64	24.31	
	4	22.69	22.53	23.20	22.49	22.55	23.09	22.03	23.54	23.21	25.30	25.26	24.97	24.79	26.25	24.12	24.74	24.64	25.30	
	5	22.22	22.65	22.47	21.79	22.55	21.64	22.08	22.87	22.56	24.38	25.02	24.92	24.92	25.58	23.27	24.60	23.55	24.40	

Legend:

Take Out No.	Duration From Start To Take Out (Hrs.)
0	0
1	3
2	20
3	59
4	89
5	138
6	252

Legend:

Take Out No.	Duration From Start To Take Out (Hrs.)
0	0
1	4
2	19
3	48
4	72
5	136
6	249

Table 6. Distribution of moisture content in the two desorption experiments.

		DESORPTION EXPERIMENT NO. 1									DESORPTION EXPERIMENT NO. 2									Moisture Content (%)
Take Out	Section	Controls (No Load)			Loaded (2.205 lbs.)			Loaded 4.410 lbs.)			Controls (No Load)			Loaded (2.205 lbs.)			Loaded (4.410 lbs.)			
		Replicate No.									Replicate No.									
No.	No.	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	
0	1	16.90	18.04	18.81	-	-	-	-	-	-	21.56	21.81	22.41	-	-	-	-	-	-	
	2	16.96	18.24	18.25	-	-	-	-	-	-	21.52	22.30	22.44	-	-	-	-	-	-	
	3	17.16	13.56	18.58	-	-	-	-	-	-	22.49	22.40	21.95	-	-	-	-	-	-	
	4	16.96	18.24	18.25	-	-	-	-	-	-	21.52	22.30	22.44	-	-	-	-	-	-	
	5	16.90	18.04	18.81	-	-	-	-	-	-	21.56	21.81	22.41	-	-	-	-	-	-	
1	1	8.96	9.04	8.88	10.21	9.82	9.55	10.15	9.17	7.94	11.27	10.60	11.30	11.90	11.48	10.65	11.80	10.26	10.64	
	2	10.00	8.98	10.22	11.69	10.99	11.93	11.41	11.25	10.00	13.95	12.58	13.41	15.06	14.49	14.76	14.26	12.83	13.98	
	3	9.83	9.94	9.70	12.13	11.91	11.98	11.75	11.32	10.01	14.08	13.31	13.83	15.90	14.80	15.38	15.22	13.65	14.22	
	4	10.00	9.98	10.22	12.17	11.85	11.91	11.65	11.78	11.16	13.95	12.58	13.41	15.49	14.51	15.09	14.48	12.94	14.36	
	5	8.96	9.02	8.88	10.34	10.26	10.32	10.21	10.13	9.67	11.27	10.60	11.30	12.18	12.10	11.61	11.67	11.10	11.79	
2	1	7.61	7.48	7.38	7.09	6.59	6.70	5.21	6.82	7.34	7.93	8.22	7.78	7.66	7.27	7.80	7.71	7.61	8.04	
	2	7.83	7.85	8.09	7.93	7.30	6.85	7.74	7.70	8.05	9.00	9.13	8.77	8.34	8.57	9.19	9.05	8.75	9.47	
	3	8.16	8.35	7.78	7.64	8.25	8.48	8.08	8.31	8.94	9.27	9.38	9.01	8.64	9.09	9.04	9.88	8.45	9.38	
	4	7.83	7.85	8.09	7.56	8.17	8.32	7.91	8.52	8.27	9.00	9.13	8.77	8.36	8.93	9.00	9.29	8.60	9.09	
	5	7.61	7.48	7.38	7.14	7.37	6.55	5.59	7.34	7.40	7.93	8.22	7.78	8.15	7.89	8.26	8.17	8.02	8.18	
3	1	6.13	5.92	6.75	6.25	7.02	6.47	5.98	6.14	5.98	6.69	7.04	6.95	6.55	6.26	6.80	6.58	6.96	6.69	
	2	6.63	6.72	6.44	7.23	7.43	7.47	7.09	6.24	7.45	7.27	6.99	7.46	7.46	7.47	6.88	7.24	7.68	7.32	
	3	6.62	6.75	6.98	7.28	7.31	7.26	7.07	7.11	6.58	6.85	7.44	7.25	7.69	7.11	7.67	7.72	7.85	7.45	
	4	6.63	6.72	6.44	7.19	6.57	7.28	7.13	7.10	6.86	7.27	6.99	7.46	7.48	7.15	7.68	7.61	7.80	7.37	
	5	6.13	5.92	6.75	7.44	7.00	7.43	7.09	6.48	6.96	6.69	7.04	6.95	7.21	7.32	7.16	6.75	7.11	7.03	
4	1	6.22	6.17	6.36	6.54	6.27	6.27	6.48	6.59	5.91	6.92	7.09	7.22	6.67	6.58	7.06	5.77	6.33	6.50	
	2	6.60	6.45	6.60	6.72	6.52	6.78	7.01	6.22	6.53	7.16	7.09	7.25	7.27	6.74	7.00	6.29	6.68	7.00	
	3	6.72	7.04	6.70	6.96	6.60	7.03	6.55	6.17	6.74	7.22	6.89	7.39	7.76	7.00	8.37	6.15	6.89	6.88	
	4	6.60	6.45	6.60	6.74	6.21	6.55	6.67	6.41	6.84	7.16	7.09	7.25	7.11	7.07	7.22	6.40	7.65	6.66	
	5	6.22	6.17	6.36	7.11	6.51	6.96	6.72	6.60	7.34	6.92	7.09	7.22	6.80	6.66	7.08	6.82	7.14	6.86	
5	1	5.95	5.36	6.10	6.20	6.54	6.52	5.23	6.60	5.81	6.47	6.53	6.35	6.32	6.48	6.37	6.57	6.37	6.42	
	2	6.22	6.21	6.12	6.50	6.56	6.40	6.52	6.98	5.77	6.51	6.50	6.44	6.45	6.40	6.58	6.43	6.04	6.79	
	3	6.51	6.12	6.16	6.30	6.99	6.26	5.08	6.45	6.54	6.70	6.73	6.37	6.52	6.86	6.57	6.60	6.35	6.42	
	4	6.22	6.21	6.12	6.51	6.72	6.17	6.45	5.20	6.52	6.51	6.50	6.44	6.40	6.59	6.51	6.31	6.75	6.30	
	5	5.95	5.36	6.10	6.74	6.54	8.80	6.68	6.94	6.19	6.47	5.53	6.35	6.51	6.63	6.54	6.57	6.37	6.52	
6	1	6.04	6.00	6.58	6.34	6.96	6.50	5.66	6.68	6.07	6.55	6.66	6.21	5.77	5.90	5.96	6.27	6.50	6.02	
	2	6.49	5.98	6.43	6.78	6.62	6.61	6.40	6.96	6.94	6.17	6.09	6.24	6.53	6.15	6.50	6.14	6.28	6.37	
	3	6.18	6.35	6.85	6.89	7.22	7.06	6.39	6.67	6.60	6.31	6.59	6.61	6.34	6.27	6.45	6.16	6.05	6.11	
	4	6.49	5.98	6.43	6.72	6.92	7.07	6.57	7.50	6.79	6.17	6.09	6.24	6.45	6.35	6.28	6.04	6.07	6.35	
	5	6.04	6.00	6.58	6.74	7.15	6.74	6.60	6.81	6.78	6.55	6.66	6.21	6.68	6.32	5.99	6.34	6.62	6.12	

Legend:	Take Out No.	Duration From Start To Take Out (Hrs.)
	0	0
	1	4
	2	21
	3	48
	4	80
	5	153
	6	223

Legend:	Take Out No.	Duration From Start To Take Out (Hrs.)
	0	0
	1	4
	2	20
	3	43
	4	71
	5	159
	6	244

Table 7. Creep deflection in the two adsorption experiments.

ADSORPTION EXPERIMENT NO. 1													ADSORPTION EXPERIMENT NO. 2																											
Take Out No.	Duration Hours	Gage No.											Take Out No.	Duration Hours	Gage No.																									
		1	2	3	4	5	6	7	8	9	10	11			12	1	2	3	4	5	6	7	8	9	10	11	12													
														Deflection (1/1000 in.)																										
1	0	169	327	169	327	169	327	169	327	169	327	169	327	1	0	166	324	166	324	166	324	166	324	166	324	166	324													
	1	171	364	174	387	200	420	210	423	215	425	212	398		1	201	400	241	450	223	420	238	433	226	415	228	428													
	2	202	405	199	410	213	448	237	452	244	483	227	434		3	201	429	272	486	245	448	270	464	252	445	247	458													
	3	211	418	216	423	226	469	258	469	267	521	241	455		4	202	442	278	502	252	460	274	476	261	457	254	470													
2	4	222	429	243	477	271	480	280	540	249	465			2	5	288	515	257	468	278	483	267	470	258	479															
	5	231	432	243	491	280	490	294	562	257	478				6	292	530	262	479	278	493	270	479	263	487															
	6	239	438	277	503	287	499	302	581	264	490				7	295	546	267	492	278	506	278	490	269	497															
	7	252	447	277	514	293	510	313	597	271	501				8	298	557	270	498	279	513	281	498	275	503															
	8	255	454	295	520	301	514	316	600	273	507				15	312	620	284	548	295	578	305	538	300	544															
	15	279	497	319	576	331	559	323	690	296	560				17	314	632	285	557	297	590	309	543	303	550															
	18	279	505	319	590	337	567	323	711	296	568				19	315	645	286	568	298	601	315	552	306	557															
	20	284	511	319	598	341	574	323	724	296	578				22	287	581	307	611	322	559	310	567																	
	3	23	319	602	341	579	384	743	322	593						25	287	594	309	624	329	568	316	574																
		24	319	604	348	579	384	743	322	593						27	287	601	313	631	329	574	318	579																
42		319	626	348	586	384	787	328	619					37	287	626	317	658	330	594	320	594																		
47		319	626	348	586	384	791	328	619					41	287	628	318	661	331	595	320	594																		
48		319	626	349	586	384	791	328	619					45	287	629	319	662	331	595	320	595																		
59		319	626	349	586	384	799	329	619					48	287	629	319	662	335	600	320	595																		
4		65					349	586	405	802	333	625			3	50					319	662	335	600	320	595														
		71					349	586	405	803	333	625				52					319	662	335	600	320	598														
		73					349	589	413	804	335	625				53					319	662	335	600	320	599														
		83					353	589	413	804	335	625				65					319	662	335	600	320	600														
	89					353	589	413	804	335	625			67						319	662	335	600	320	600															
	5	95								413	804	335	625				4	68								319	662	335	600	320	600									
		97								413	804	335	625					71					319	662	335	600	320	602												
		111								413	804	335	625					72					319	662	335	600	320	602												
		120								415	804	335	625					75					342	605	320	609														
		134								415	804	335	625					76					342	607	323	614														
138									415	804	335	625			85						349	660	332	622																
165										335	625			88						364	675	340	633																	
167										336	625			90						377	684	353	647																	
168										336	634			93						382	692	361	658																	
179										343	640			96						392	713	372	672																	
186									343	640			99					411	735	390	685																			
189									343	640			101					414	742	398	693																			
214									343	640			109					434	771	404	702																			
238									343	640			116					434	771	405	711																			
252									343	640			126					434	771	405	717																			
Total:		211	418	284	511	319	626	353	589	415	804	343	640	5	136					434	771	417	719																	
Legend: Odd No. gages on light loaded beams Even No. gages on heavy loaded beams.														6	144													144												
															147													147												
															156													156												
															164													164												
															166													166												
															167													167												
															184													184												
															208													208												
															232													232												
															241													241												
														249													249													
Total:														202	442	315	645	287	629	319	662	434	771	435	867	Total:														

Table 8. Creep deflection in the two desorption experiments.

DESORPTION EXPERIMENT NO. 1													DESORPTION EXPERIMENT NO. 2														
Take Out No.	Duration Hours	Gage No.											Take Out No.	Duration Hours	Gage No.												
		1	2	3	4	5	6	7	8	9	10	11			12	1	2	3	4	5	6	7	8	9	10	11	12
Deflection (1/1000 in.)													Deflection (0.001 in.)														
1	0	171	341	171	341	171	341	171	341	171	341	171	341	1	0	164	348	164	348	164	348	164	348	164	348	164	348
	1	171	429	233	438	173	425	188	383	196	448	189	456		1	166	448	186	511	219	482	167	526	206	506	207	443
	2	205	441	242	453	201	439	208	403	205	462	201	468		2	247	494	227	570	279	—	207	547	252	558	251	533
	3	222	451	250	465	213	449	218	423	210	472	211	481		3	278	522	247	611	309	602	225	598	270	582	272	553
2	4	239	462	261	479	224	460	231	434	217	486	224	493	4	297	535	257	624	330	638	233	613	279	598	280	567	
	6			281	488	257	468	231	442	233	494	236	502	5			267	637	351	668	243	620	288	605	292	583	
	7			285	496	257	474	235	449	237	503	240	509	6			273	645	363	685	243	639	294	619	298	592	
	8			288	501	257	477	238	455	238	508	241	513	7			279	654	371	697	251	649	299	629	303	598	
3	16			309	531	277	505	260	483	253	538	272	541	16			312	703	421	775	278	706	334	683	341	648	
	18			312	536	277	510	266	488	253	542	275	550	17			315	708	423	781	282	712	336	684	343	652	
	21			317	543	281	517	272	496	253	549	278	556	19			318	711	425	788	282	720	341	691	348	658	
	25			296	522	278	504	268	554	285	564	20			321	715	427	795	283	726	344	698	352	662			
4	30			300	530	287	513	277	562	290	573	21					443	796	283	729	346	698	353	664			
	33			303	535	291	518	278	566	295	578	23					456	806	288	738	349	700	354	672			
	43			308	546	301	531	284	577	305	589	26					464	817	290	746	353	718	359	678			
	48			313	549	304	534	289	579	307	593	27					467	820	293	749	355	719	362	680			
5	52					309	539	295	582	312	598	30					473	828	297	755	359	721	366	686			
	54					310	541	295	582	313	599	38					487	846	311	771	367	737	376	689			
	64					317	547	300	593	318	606	41					491	851	314	776	371	742	379	693			
	70					321	551	304	595	321	610	43					494	856	317	779	372	745	382	697			
6	75					324	554	306	596	324	613	46							321	780	374	746	383	700			
	80					326	556	307	596	325	616	51							326	786	378	748	386	705			
	85								314	601	331	620	52							327	787	379	749	387	706		
	94								314	601	331	621	62							334	797	386	762	394	714		
7	101								315	601	332	625	63							335	797	387	763	394	715		
	117								318	601	334	630	68							338	802	390	766	398	718		
	122								320	616	334	631	71							340	804	391	768	399	720		
	140								322	616	340	637	74									391	768	407	739		
8	149								323	616	343	638	76									391	768	408	743		
	153								324	616	344	639	78									392	770	409	745		
	170										344	640	89									393	776	414	767		
	174										345	641	92									393	777	415	769		
9	185										346	644	103									398	780	420	774		
	193										346	644	112									398	781	423	777		
	196										346	644	116									405	781	424	778		
	208										349	646	123									407	781	426	782		
10	214										349	648	124									408	792	427	784		
	222										350	649	134									408	795	429	785		
	223										351	649	137									408	796	432	786		
												351	649	141									408	796	432	787	
11													145									411	797	433	788		
													159									411	797	434	791		
													162														
													166														
12													167														
													168														
													172														
													182														
13													185														
													187														
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													220														
													223														
16													224														
													232														
													237														
													243														
17													244														

Legend: Odd No. Gages on light loaded beams.
Even No. Gages on heavy loaded beams.

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Table 9. Analyses of variance.

F - Probability distribution

xx - Highly significant (significant at 99% level)

x - Significant (significant at 90% level)

N.S. - Not significant

DESORPTION EXPERIMENTS NO. 1 and 2					ADSORPTION EXPERIMENTS NO. 1 and 2			Legend: Source of Variation; 1 Experiment (D ₁ , D ₂ or A ₁ , A ₂) 2 Load Levels (control, light, heavy) 3 Take Outs 4 Position of M.C. (sections)
Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F	Sums of Squares	Mean Squares	F	
1	1	69.39481	69.39481	476.875 **	41.88361	41.88361	105.523 **	
2	2	11.55164	5.77582	39.691 **	0.03867	0.01933	0.049 N.S.	
3	5	1868.84209	373.76842	2568.502 **	11301.91870	2260.38373	5678.928 **	
4	4	62.20750	15.55187	106.871 **	47.19033	11.79758	29.640 **	
12	2	3.55203	1.77601	12.205 **	0.14470	0.07235	0.182 N.S.	
13	5	120.49876	24.09975	165.611 **	150.14575	30.02915	75.444 **	
14	4	2.69329	0.67332	4.627 **	0.66104	0.16526	0.415 N.S.	
23	10	26.20850	2.62085	18.010 **	26.10059	2.61006	6.557 **	
24	8	4.49518	0.56190	3.861 **	7.42621	0.92828	2.332 *	
34	20	72.67567	3.63378	24.971 **	201.72363	10.08618	25.340 **	
123	10	3.81726	0.38173	2.623 **	15.42029	1.54203	3.874 **	
124	8	1.15101	0.14388	0.989 N.S.	1.16215	0.14527	0.365 N.S.	
134	20	11.49213	0.57461	3.949 **	2.81848	0.14092	0.354 N.S.	
234	40	6.84782	0.17120	1.176 N.S.	5.64294	0.14107	0.354 N.S.	
1234	40	3.50806	0.08770	0.603 N.S.	2.83154	0.07079	0.018 N.S.	
Within Replicates	360	52.38899	0.14552		143.29016	0.39803		
Total	539	2321.32462			11948.39856			
DESORPTION EXPERIMENT NO. 1					DESORPTION EXPERIMENT NO. 2			Legend: Source of Variation; 1 Load Levels (control, light, heavy) 2 Take Outs 3 Position of M.C. (sections)
Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F	Sums of Squares	Mean Squares	F	
1	2	13.43314	6.71657	37.833 **	1.67051	0.83525	7.358 **	
2	5	528.47133	105.69427	595.360 **	1460.86957	292.17391	2573.766 **	
3	4	22.08621	5.52155	31.102 **	42.81456	10.70364	94.289 **	
12	10	17.57397	1.75740	9.899 **	12.45177	1.24518	10.969 **	
13	8	3.46774	0.43347	2.442 *	2.17846	0.27231	2.399 *	
23	20	18.47725	0.92386	5.204 **	65.69052	3.28453	28.933 **	
123	40	6.75742	0.16894	0.952 N.S.	3.59979	0.08999	0.793 N.S.	
Within Replicates	180	31.95571	0.17753		20.43332	0.11352		
Total	269	642.22276			1609.70847			
ADSORPTION EXPERIMENT NO. 1					ADSORPTION EXPERIMENT NO. 2			
Source of Variation	Degree of Freedom	Sums of Squares	Mean Squares	F	Sums of Squares	Mean Squares	F	
1	2	0.01691	0.00846	0.030 N.S.	0.16645	0.08323	0.163 N.S.	
2	5	4939.34729	987.86945	3459.048 **	6512.71710	1302.54341	2551.705 **	
3	4	23.91440	5.97860	20.934 **	23.93697	5.98424	11.723 **	
12	10	14.44531	1.44453	5.058 **	27.07605	2.70760	5.304 **	
13	8	3.71706	0.46463	1.627 N.S.	4.87131	0.60891	1.193 N.S.	
23	20	107.81287	5.39064	18.875 **	96.73022	4.83651	9.475 **	
123	40	3.01807	0.07545	0.264 N.S.	5.46338	0.13658	0.268 N.S.	
Within Replicates	180	51.40669	0.28559		91.88358	0.51046		
Total	269	5143.67859			6762.84503			

adsorption experiments it was approximately 2 to 3%. This difference suggested that all the four experiments should be analyzed individually with regard to moisture content.

The next step prior to any further analyses was to test differences between main effects and interactions among variable. An analysis of variance was made for each experiment. Table 9 shows the detailed results of these calculations. They indicated that highly significant differences were found for positional moisture content, load level and load duration. Significant interactions were found to exist between: (1) positional moisture content and load duration, (2) positional moisture content and load level, (3) load level (creep deflection) and positional moisture content, and (4) load level (creep deflection) and load duration.

2/ Analysis of Experimental Error in Moisture Content Measurements

Since the main objective of this investigation was concerned with moisture distribution in wooden beams under constant bending load, it was necessary to check the accuracy of the positional moisture content data. During the experiments the accuracy of positional moisture content was assured by proper replications. This meant that the average values of the three replicates had to vary less than the individual replicates themselves. Such difference can be explained by the variability of the individual weight measurements which are influenced of the experimental errors. In these experiments,

the experimental error had three sources: (1) Errors due to limitations in the accuracy of measurements; (2) errors due to natural variability of wood; and (3) errors originating from the variability of containers weights during the period of measurement. The first and second sources are true experimental errors. However, variations in container weight had to be analyzed to avoid gross error in weighing because of the large weight of the containers as compared to the weight of the wood samples, and also because of the expected small weight differences that had to be detected in this study. A short study was set up to analyze the variations in container weights. The results of this study are given in Table 10.

Table 10. Variations in Container Weight.

Experiment	Mean Container Weight (gm)	Standard Deviation (gm)	Coefficient of Variation (%)
Adsorption 1	7.33181	0.0014503	0.020
Adsorption 2	7.33398	0.0016253	0.022
Desorption 1	7.33183	0.0018367	0.025
Desorption 2	7.33225	0.0015240	0.021

Since the coefficients of variation were small for the container weights in each of the four experiments, their absolute variation was small enough to allow the detection of minor moisture content differences due to the different stress conditions in the wood. Therefore, the conclusion can be drawn that the magnitude of error

due to the variability in container weight was not greater than the true experimental errors. Consequently, the following calculations have an experimentally sound basis.

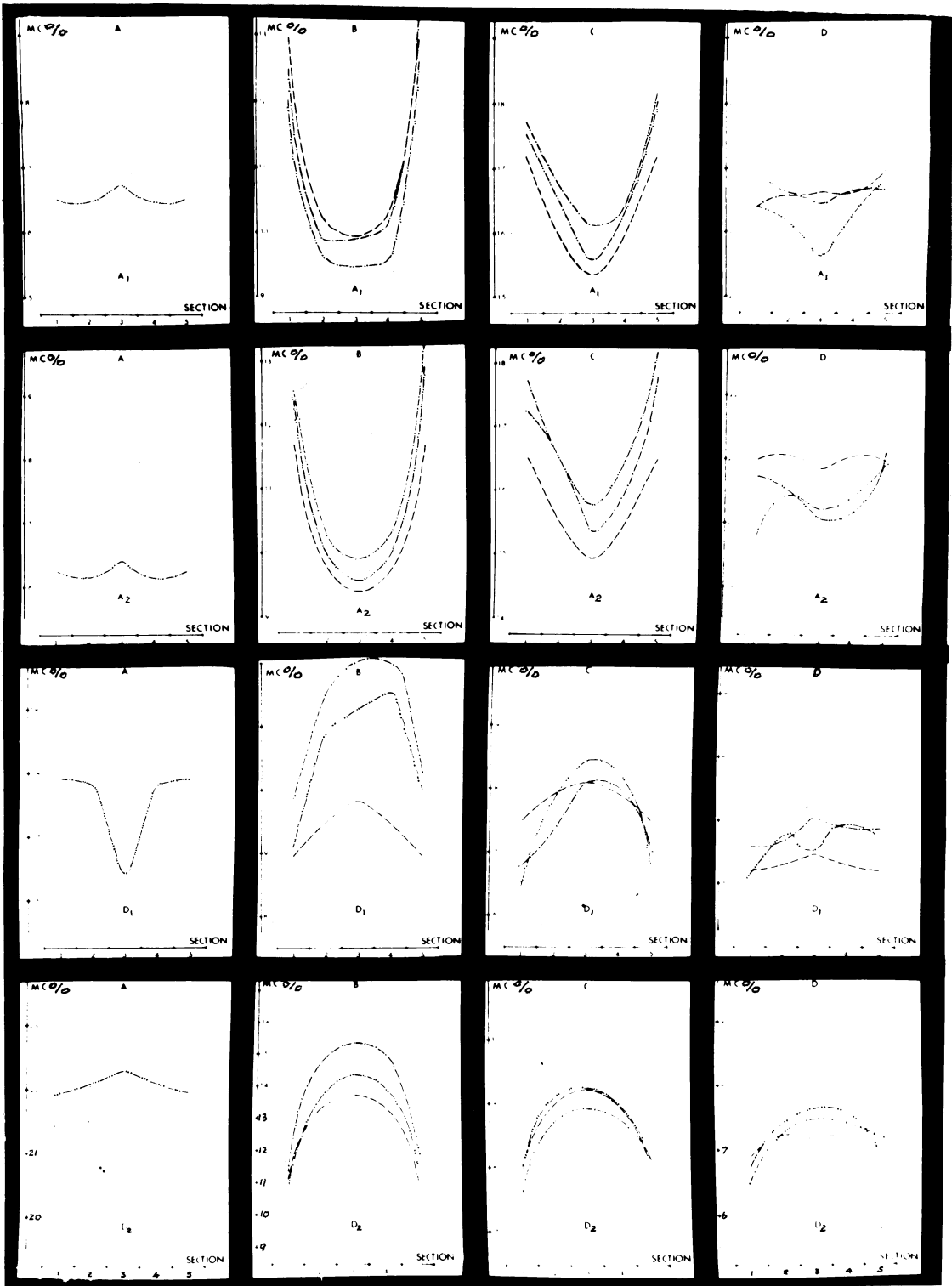
3/ Moisture Distribution as a Function of Time

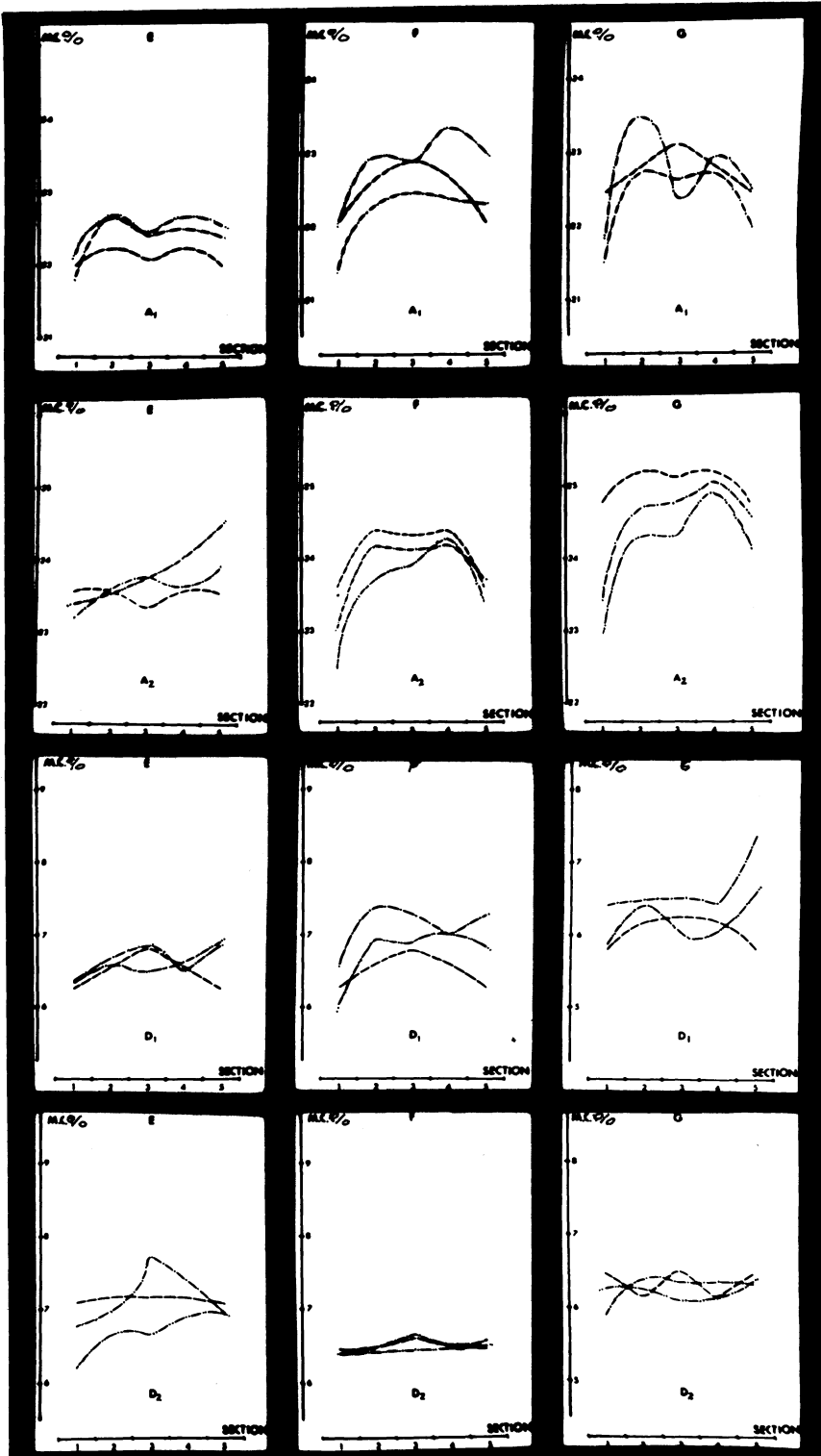
Using the five average values for the positional moisture content of three replicate beams, moisture distribution curves were constructed for each load level at each take out. Those curves are presented in Figure 12 a and 12 b. The data on which these curves are based are given in Table 5 and 6.

The analysis of moisture distribution curves and data indicated that the higher rate of moisture content changes occurred in the outer sections of the beams. This phenomenon could be explained by the differences between vapor pressure in the chamber and that of the moisture in the test specimen. The change in moisture gradients indicated a decreasing tendency with time, which is associated with diffusion of moisture in wood. In flexed wood, moisture changes were slower than in non-flexed wood because different rates of moisture diffusion as a result of the application of mechanical stresses in accordance with Barkas (5). There appeared to be a slightly asymmetric moisture distribution in the stressed beams as shown in Figure 12 a and 12 b. In other words, the acting compressive and tensile stresses affected the positional moisture contents to different extents. The moisture content in wood under tension was

Figure 12 a, 12 b. Average moisture distribution in beams at initial stage and at the six consecutive take outs.

- A₁ - Adsorption first experiment
- A₂ - Adsorption second experiment
- D₁ - Desorption first experiment
- D₂ - Desorption second experiment
- A - Average moisture distribution at initial stage (%)
- B - Average moisture distribution at take out 1 (%)
- C - Average moisture distribution at take out 2 (%)
- D - Average moisture distribution at take out 3 (%)
- E - Average moisture distribution at take out 4 (%)
- F - Average moisture distribution at take out 5 (%)
- G - Average moisture distribution at take out 6 (%)
- Average moisture distribution at initial stage (%)
- Average moisture distribution in controls (%)
- Average moisture distribution under light load (%)
- Average moisture distribution under heavy load (%)





higher than that in wood under compression. The magnitude of stresses within the elastic range did not appear to affect the positional moisture content markedly. In wood under light load level (2.205 lbs.), the average moisture content difference between extreme sections was 0.58% with a maximum range of 1.10%. Whereas under heavy load level (4.410 lbs.), the average difference was 0.59% with a maximum range of 1.20%.

In order to test the significance of these differences, the moisture content of sections in compression and tension in the flexed beams was compared, using t - tests. The method and the detailed results of this calculations are given in Table 11. The results of t - tests indicated that the average difference between the moisture content of the outer sections was significant. The moisture contents of the next inner sections were compared also. However, the results were not significant. Therefore, the results of the t - tests indicated that significant differences between the moisture content of sections in compression and tension in stressed beams, only occur between the extreme sections, where these stresses are at maximum. Since these stresses decrease towards the neutral axis the differences were so small that they could not be proven significant by statistical methods.

The mechanisms which were responsible for the above phenomenon in wood may be explained by the following theories.

Table 11. Comparison of moisture content in the extreme sections of stressed beams using t-tests.

t - Probability distribution

DESORPTION EXPERIMENT NO. 1							DESORPTION EXPERIMENT NO. 2						
Grouping	Loaded (2,205 lbs.)						Loaded (2,205 lbs.)						
	D BAR	SD BAR	T	N	TABLE "t"	SIGNIFICANT AT	D BAR	SD BAR	T	N	TABLE "t"	SIGNIFICANT AT	
Take Out 1	0.4667	0.184782	2.4173	3	1.886	80.0%	0.6200	0.196299	3.1584	3	2.920	90.0%	
" - 2	0.2267	0.282627	0.8020	3	—	N. S.	0.5267	0.068074	10.9553	3	9.925	99.0%	
" - 3	0.7100	0.370990	1.9138	3	1.886	80.0%	0.6933	0.202759	3.4195	3	2.920	90.0%	
" - 4	0.4933	0.129951	3.7974	3	2.920	90.0%	0.0767	0.011798	2.4111	3	1.886	80.0%	
" - 5	0.9400	0.687895	1.3663	3	1.061	60.0%	0.1700	0.011547	14.7224	3	9.925	99.0%	
" - 6	0.2767	0.061331	4.3684	3	4.303	95.0%	0.4533	0.254580	1.7807	3	1.886	70.0%	
All 6 Take Outs	0.5156	0.134864	3.8228	18	2.898	99.0%	0.4233	0.076909	5.5043	18	3.965	99.0%	
Loaded (4,410 lbs.)							Loaded (4,410 lbs.)						
Take Out 1	0.9167	0.482574	1.8995	3	1.886	80.0%	0.6033	0.374270	1.6120	3	1.886	70.0%	
" - 2	0.3400	0.117189	2.9013	3	1.886	80.0%	0.3367	0.099387	3.3874	3	2.920	90.0%	
" - 3	0.8100	0.237978	3.4037	3	2.920	90.0%	0.2200	0.060277	3.6498	3	2.920	90.0%	
" - 4	0.5600	0.440038	1.2726	3	1.061	60.0%	0.7400	0.202237	3.6591	3	2.920	90.0%	
" - 5	0.7213	0.363517	1.9898	3	1.886	80.0%	0.0333	0.033333	1.0000	3	0.816	50.0%	
" - 6	0.5911	0.240991	2.4620	3	1.886	80.0%	0.0967	0.014530	6.6531	3	4.303	95.0%	
All 6 Take Outs	0.6572	0.124593	5.2750	18	3.965	99.0%	0.3383	0.087929	3.8478	18	2.898	99.0%	
Loaded (2,205 and 4,410 lbs.)							Loaded (2,205 and 4,410 lbs.)						
Take Out 1	0.6817	0.253869	2.6851	6	2.571	95.0%	0.6117	0.189040	3.2556	6	2.571	95.0%	
" - 2	0.2813	0.139156	2.0161	6	2.015	90.0%	0.4317	0.065137	6.6271	6	4.032	99.0%	
" - 3	0.7690	0.198377	3.8111	6	3.365	98.0%	0.4567	0.141955	3.2170	6	2.571	95.0%	
" - 4	0.5267	0.205729	2.5800	6	2.015	90.0%	0.4083	0.174307	2.3426	6	2.015	90.0%	
" - 5	0.8317	0.351306	2.3674	6	2.015	90.0%	0.1017	0.034392	2.9562	6	2.571	95.0%	
" - 6	0.4350	0.132029	3.2947	6	2.571	95.0%	0.2750	0.139158	1.9762	6	1.476	80.0%	
All 6 Take Outs	0.3808	0.058015	6.5644	36	3.599	99.0%	0.5864	0.091272	6.4247	36	3.599	99.0%	
ADSORPTION EXPERIMENT NO. 1							ADSORPTION EXPERIMENT NO. 2						
Grouping	Loaded (2,205 lbs.)						Loaded (2,205 lbs.)						
	D BAR	SD BAR	T	N	TABLE "t"	SIGNIFICANT AT	D BAR	SD BAR	T	N	TABLE "t"	SIGNIFICANT AT	
Take Out 1	0.7367	0.265978	2.7896	3	1.886	80.0%	0.8300	0.245561	3.3800	3	2.920	90.0%	
" - 2	0.4313	0.201770	2.1477	3	1.886	80.0%	0.5667	0.254711	2.2247	3	1.886	80.0%	
" - 3	0.2633	0.259829	1.0135	3	0.816	50.0%	1.1633	0.259829	4.4773	3	4.303	95.0%	
" - 4	0.5567	0.151442	3.6279	3	2.920	90.0%	0.7233	0.253136	2.8575	3	1.886	80.0%	
" - 5	0.8967	0.463657	1.9339	3	1.886	80.0%	0.6800	0.370405	1.8358	3	1.886	70.0%	
" - 6	0.4567	0.463657	0.9849	3	0.816	50.0%	1.1400	0.276104	4.1289	3	2.920	90.0%	
All 6 Take Outs	0.5572	0.122242	4.5584	18	3.965	99.0%	0.8506	0.110626	7.6885	18	3.965	99.0%	
Loaded (4,410 lbs.)							Loaded (4,410 lbs.)						
Take Out 1	0.5933	0.352152	1.6849	3	1.886	70.0%	0.5467	0.576927	0.9475	3	0.816	50.0%	
" - 2	0.5167	0.396330	1.3036	3	1.061	60.0%	0.4367	0.197005	2.2165	3	1.886	80.0%	
" - 3	0.4333	0.557982	0.7766	3	—	N. S.	0.4000	0.126623	3.1590	3	2.920	90.0%	
" - 4	0.3900	0.420357	0.9278	3	0.816	50.0%	1.1000	0.311929	3.5264	3	2.920	90.0%	
" - 5	0.9200	0.671590	1.3699	3	1.061	60.0%	0.9067	0.202512	4.4771	3	4.303	95.0%	
" - 6	0.6500	0.386911	1.6800	3	1.886	70.0%	1.2367	0.445733	2.7745	3	1.886	80.0%	
All 6 Take Outs	0.5839	0.169253	3.4498	18	2.898	99.0%	0.7711	0.143233	5.3836	18	3.965	99.0%	
Loaded (2,205 and 4,410 lbs.)							Loaded (2,205 and 4,410 lbs.)						
Take Out 1	0.6650	0.199946	3.3259	6	2.571	95.0%	0.6883	0.287477	2.3944	6	2.015	90.0%	
" - 2	0.4750	0.199762	2.3778	6	2.015	90.0%	0.5017	0.146911	3.4148	6	3.365	98.0%	
" - 3	0.3483	0.277878	1.2535	6	1.156	70.0%	0.7817	0.214109	3.6508	6	3.365	98.0%	
" - 4	0.4733	0.203563	2.3252	6	2.015	90.0%	0.9117	0.198417	4.5947	6	4.032	99.0%	
" - 5	0.9083	0.365006	2.4885	6	2.015	90.0%	0.7933	0.195477	4.0585	6	4.032	99.0%	
" - 6	0.5533	0.273504	2.0231	6	2.015	90.0%	1.1883	0.235477	5.0465	6	4.032	99.0%	
All 6 Take Outs	0.5706	0.102913	5.5441	36	3.599	99.0%	0.8108	0.089440	9.0656	36	3.599	99.0%	
ADSORPTION EXPERIMENTS NO. 1 & 2							DESORPTION EXPERIMENTS NO. 1 & 2						
Grouping	Loaded (2,205 lbs.)						Loaded (2,205 lbs.)						
	D BAR	SD BAR	T	N	TABLE "t"	SIGNIFICANT AT	D BAR	SD BAR	T	N	TABLE "t"	SIGNIFICANT AT	
Take Out 1	0.7833	0.163231	4.7989	6	4.032	99.0%	0.5333	0.126640	4.2114	6	4.032	99.0%	
" - 2	0.5000	0.148346	3.3705	6	3.365	98.0%	0.3767	0.144699	2.6031	6	2.571	95.0%	
" - 3	0.7133	0.259816	2.7455	6	2.571	95.0%	0.7017	0.189110	3.7106	6	3.368	98.0%	
" - 4	0.6400	0.137526	4.6537	6	4.032	99.0%	0.2850	0.110717	2.5741	6	2.571	95.0%	
" - 5	0.7883	0.269783	2.9221	6	2.571	95.0%	0.5550	0.352579	1.5741	6	1.476	80.0%	
" - 6	0.7983	0.285639	2.7949	6	2.571	95.0%	0.3650	0.123794	2.9484	6	2.571	95.0%	
All 6 Take Outs	0.7039	0.084946	8.2863	36	3.599	99.0%	0.4694	0.078905	6.1042	36	3.599	99.0%	
Loaded (4,410 lbs.)							Loaded (4,410 lbs.)						
Take Out 1	0.5700	0.302457	1.8846	6	1.476	80.0%	0.7600	0.281957	2.6952	6	2.571	95.0%	
" - 2	0.4767	0.198740	2.3984	6	2.015	90.0%	0.3383	0.068722	4.9232	6	4.032	99.0%	
" - 3	0.4167	0.255990	1.6277	6	1.476	80.0%	0.5150	0.171634	3.0006	6	2.571	95.0%	
" - 4	0.7450	0.282852	2.6339	6	2.511	95.0%	0.6500	0.220288	2.9507	6	2.571	95.0%	
" - 5	0.9133	0.313716	2.9113	6	2.571	95.0%	0.3783	0.224624	1.6843	6	1.476	80.0%	
" - 6	0.9433	0.294762	3.2003	6	2.571	95.0%	0.3450	0.154892	2.2274	6	2.015	90.0%	
All 6 Take Outs	0.6725	0.110407	6.1364	36	3.599	99.0%	0.4978	0.079837	6.2349	36	3.599	99.0%	
Loaded (2,205 and 4,410 lbs.)							Loaded (2,205 and 4,410 lbs.)						
Take Out 1	0.6767	0.166975	4.0525	12	3.106	99.0%	0.6497	0.151264	4.2751	12	3.106	99.0%	
" - 2	0.4883	0.118682	4.1285	12	3.106	99.0%	0.3575	0.076586	4.6680	12	4.437	99.0%	
" - 3	0.5650	0.179543	3.1469	12	3.106	99.0%	0.6083	0.124960	4.8682	12	4.437	99.0%	
" - 4	0.6925	0.150771	4.5930	12	4.437	99.0%	0.4675	0.129779	3.6023	12	3.106	99.0%	
" - 5	0.8505	0.198152	4.2938	12	3.106	99.0%	0.4667	0.201070	2.3209	12	2.201	95.0%	
" - 6	0.8707	0.196894	4.4228	12	3.106	99.0%	0.3550	0.094576	3.7536	12	3.106	99.0%	
All 6 Take Outs	0.6907	0.069177	9.9844	72	3.460	99.0%	0.4836	0.055061	8.7833	72	3.460	99.0%	

Legend: D BAR - Average difference
SD BAR - Standard error of difference.

The cellulose skeleton of woody plants is composed of crystalline and amorphous regions. The cellulose in these two regions is built of microfibrils, which under stress conditions could be represented as helical springs as suggested by Cowdrey and Preston (11). Accepting this spring model, the response of microfibrils due to bending stresses can be analysed. In the crystalline region microfibrils in tension tend to increase their volumetric dimensions, while these dimensions tend to decrease in compression. Since load levels were in the lower part of the elastic range, the diameter change and the partial deflection of a particular microfibril are negligible. Volume changes may result from the slipping of cellulose chains within the microfibrils, or from possible hydrogen bond transfer. These changes in volume should result in space for water molecules according to their magnitude. If now we visualize the amorphous regions, similar conclusions can be drawn as those for the crystalline region. Here, the acting compressive forces tend to reduce the space among microfibrils, while the tensile forces tend to create the opposite effect. There is also a possibility of changing the volumetric dimensions due to acting forces. The total volume change here again provides space for water molecules according to its magnitude. The volume change can be accounted for by a microfibrillar orientation due to stresses, and possible hydrogen bond transfer.

The crystalline region probably does not take up or lose moisture readily because of the strong complex chemical bonds between cellulose chains prohibiting free movement. Whereas moisture transfer is quite possible in the amorphous regions due to its microfibrillar orientation, and relatively low strength and loose structure.

The final conclusion concerning this theory can be summarized as follows: Moisture content differences between the extreme sections of stressed beams are due to compressive and tensile stresses which set up dimensional changes in the amorphous regions between microfibrils.

Since both load levels in this investigation were selected in the lower portion of the elastic range, the conclusions can be drawn that the phenomenon above is reversible to some extent in time, as was confirmed by Barkas (5), Bello (7), Knight and Newall (28).

On the basis of the P. V. diagram (5) a thermodynamic consideration of moisture content difference due to tensile and compressive stresses can be analyzed. This theory is based on the properties of a perfectly elastic gel under hydrostatic and directional stresses. The P. V. diagram shows a gel with unit dry weight under different magnitudes of swelling and stresses (Figure 3). The discussion of this diagram is based on the ideas described by Barkas (5).

The gel is compressible along (VV'). If the gel will take up some moisture (M_A), its volume (VA) increases to (AA'). The same is true for (BB'), etc. Each gel at each moisture content was

treated separately by Barkas. He found that the bulk modulus increases by increasing pressure and by decreasing moisture content. The pressure under constant stress along (A D) increases with increasing moisture content. On the basis of Porter's equation ($S_p dp_m = U_{p_0} d p_0 = vdh$, where S_p is the differential sorption, or the volume increase in the solution per unit increase in moisture content, U_{p_0} is the specific volume of the water under constant pressure P_0 , and V is the specific volume of the vapor under a pressure h .), it can be seen that the vapor pressure also rises if a gel at constant moisture content ((M_A) , (M_B) etc.) is subjected to an increasing stress along AA' , BB' etc. The points with the same vapor pressure on the (P, V) diagram are represented by lines h_A , h_B , etc. If a gel swells under stress, it will take up some moisture which would result in a volume change. Figure 3 also shows that on increasing the surrounding humidity, a gel, such as wood, will take up less moisture under stress than when it is stress-free. Therefore, if stress is applied to wood, its moisture content will tend to decrease in comparison with a stress-free wood. The changes in moisture content of wood under stress will cause shrinking in compression and swelling in tension. The total dimensional change can be looked upon as the result of elastic strain and shrinking or swelling due to moisture content change.

Observations have been gathered from experiments where the direction of stresses was perpendicular to the grain. Barkas'

results (5) were found in good agreement with Bello (7) along that line.

If bending is visualized where stresses are applied parallel to grain the following conclusions can be drawn: Since swelling and shrinking in this direction are negligible, and since the results of this experiment indicated that moisture content differences were in the same magnitude as those of Barkas (5) and Bello (7), one may conclude that the directional stresses may be replaced by acting external forces to create the same effect.

A summary of this theory may be expressed as follows: In wood while under flexure the acting external forces may be responsible for the differences between the moisture contents of sections in compression and tension. This conclusion is in good agreement with that of Stern (37) and Dietz (14), stating that the strain was found to be higher on the tension faces of beams than those on the compression faces. In reference to that, the strain difference between the tension and compression of outer sections in flexed beams is probably responsible for the moisture content difference observed between those sections. The findings of Stern and Dietz are appear to be in agreement with Bach-Baumann and Newling-Trayer fiber theories, as summarized by Dietz (14). According to these fiber theories the strain in the wood fibers are increasing from the neutral axis toward the surfaces of flexed beam in both compression and tension sides. The wood fibers in compression tend to buckle due to the bending load applied. The fiber less stressed

in compression can give some support to their neighbor fibers against the buckling influence. The magnitude of support is increasing toward the neutral axis. In tension, the wood fibers have no tendency to buckle. Upon visualizing the shift of the neutral axis toward the tension side of the beam, it is evident that a relative decrease of strain in the compression fibers and a corresponding increase in the tension fibers must take place. These theories above were found in disagreement somewhat with those of Australian investigators (2, 15, 24).

In wood under bending the experimental moisture content data with regard to sections stressed in compression and tension showed significant differences. These data were verified by both experimental and theoretical considerations. In light of this, a further analysis was conducted for the representation of positional moisture content in the outer sections as a function of the duration of load application. The curves, obtained by using the least squares method and those which were found to fit best for each group of data are shown in Figures 13, 14, and 15. By observing the high "R" (correlation coefficient) values, it can be seen that all curves represented well the relationship between positional moisture content and duration of load application for all groups of data. All curves for desorption showed similar trends following a hyperbolic function; whereas in adsorption, a logarithmic function was found to fit the data best. Curves representing the relationship between moisture content in

Figure 13. Relationship between moisture content and duration of load application in the outer sections of control beams.

A_{1c} - Adsorption first experiment - control

A_{2c} - Adsorption second experiment - control

D_{1c} - Desorption first experiment - control

D_{2c} - Desorption second experiment - control

M.C. - Moisture content in the extreme sections (%)

t - Time (hours)

R - Correlation coefficient

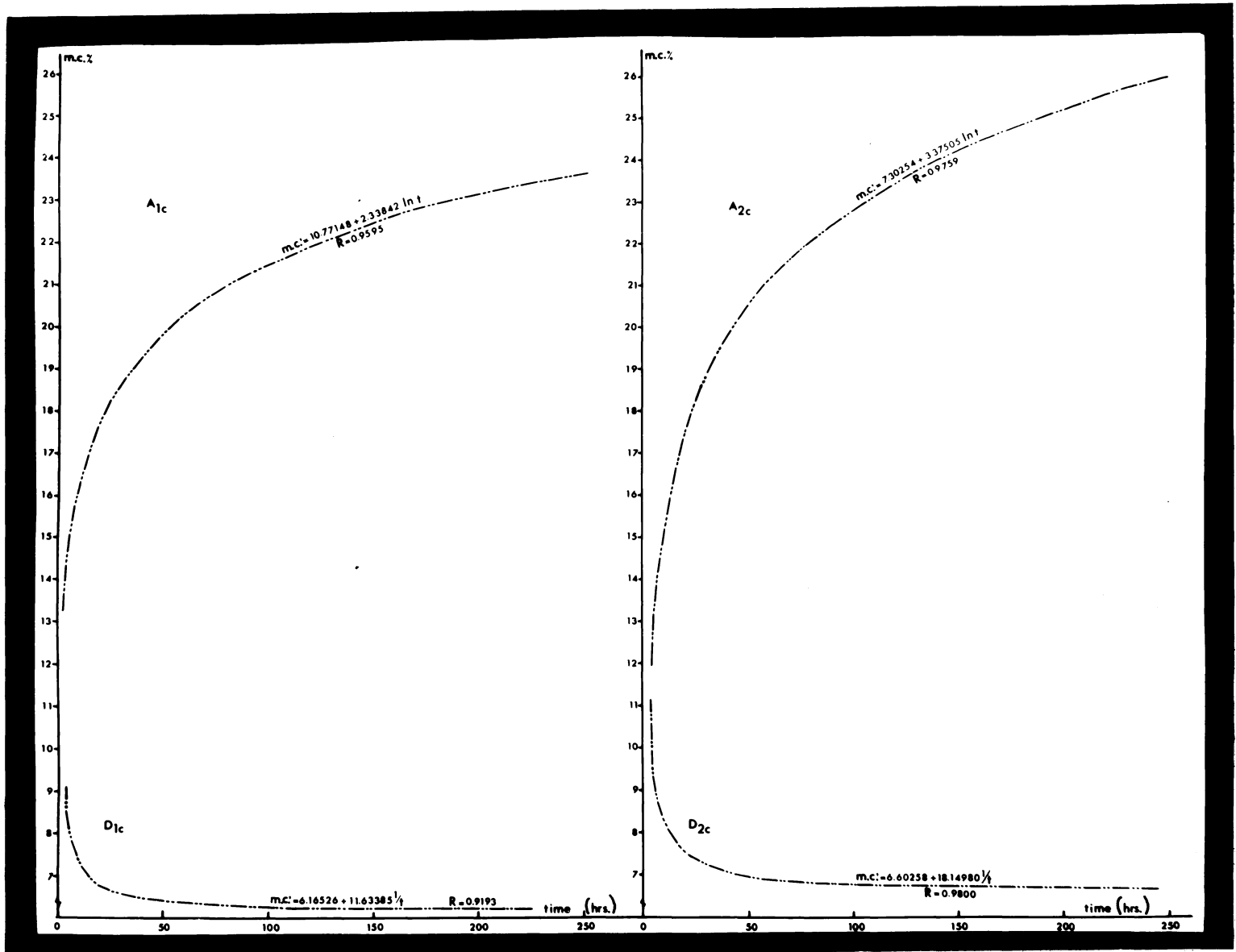


Figure 14. Relationship between moisture content and duration of load application in the outer sections of beams under light load.

A_{11} - Adsorption first experiment - light load

A_{21} - Adsorption second experiment - light load

D_{11} - Desorption first experiment - light load

D_{21} - Desorption second experiment - light load

M.C.* - Moisture content of sections in tension (%)

M.C.' - Moisture content of sections in compression (%)

t - Time (hours)

R - Correlation coefficient

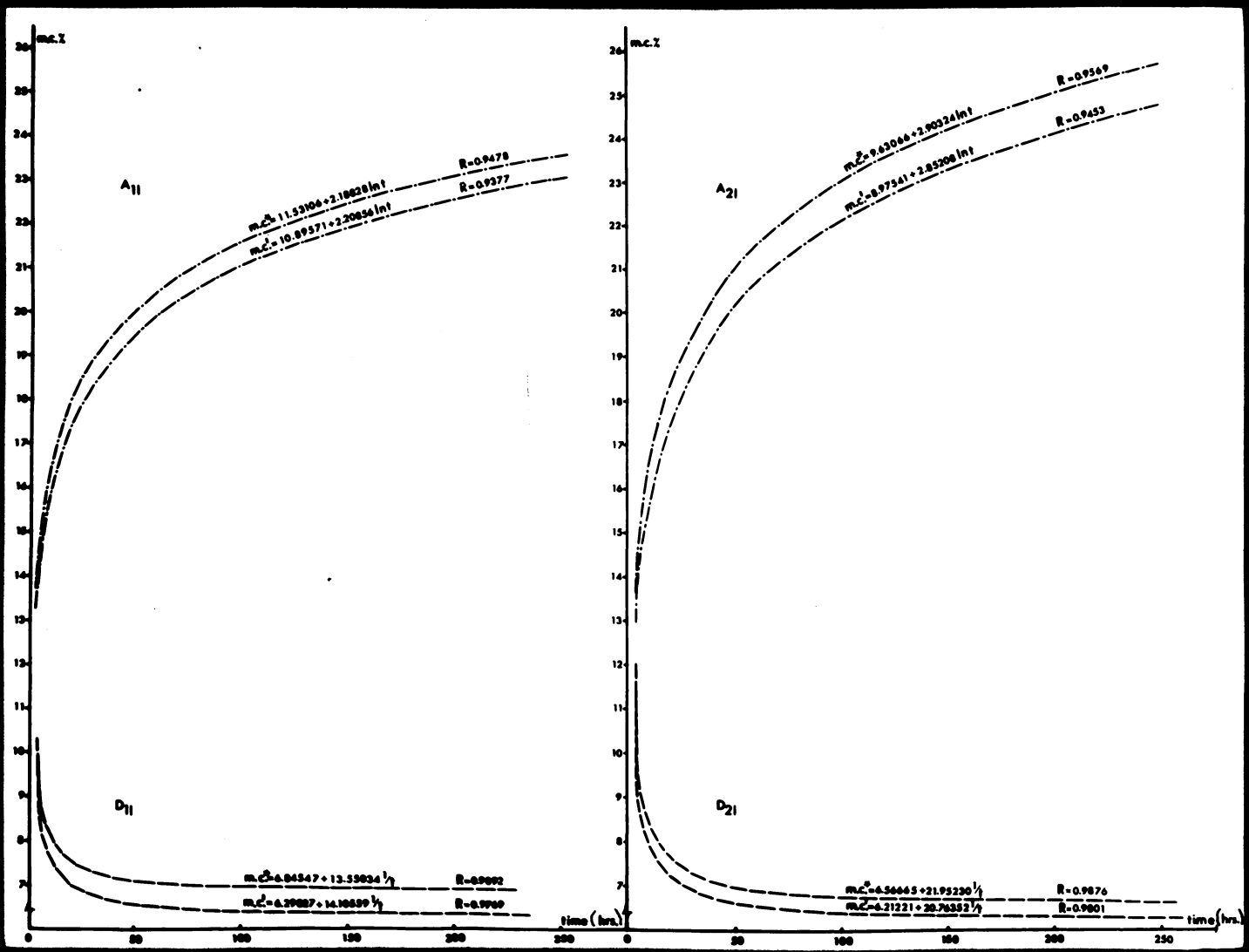


Figure 15. Relationship between moisture content and duration of load application in the outer sections of beams under heavy load.

A_{1h} - Adsorption first experiment - heavy load

A_{2h} - Adsorption second experiment - heavy load

D_{1h} - Desorption first experiment - heavy load

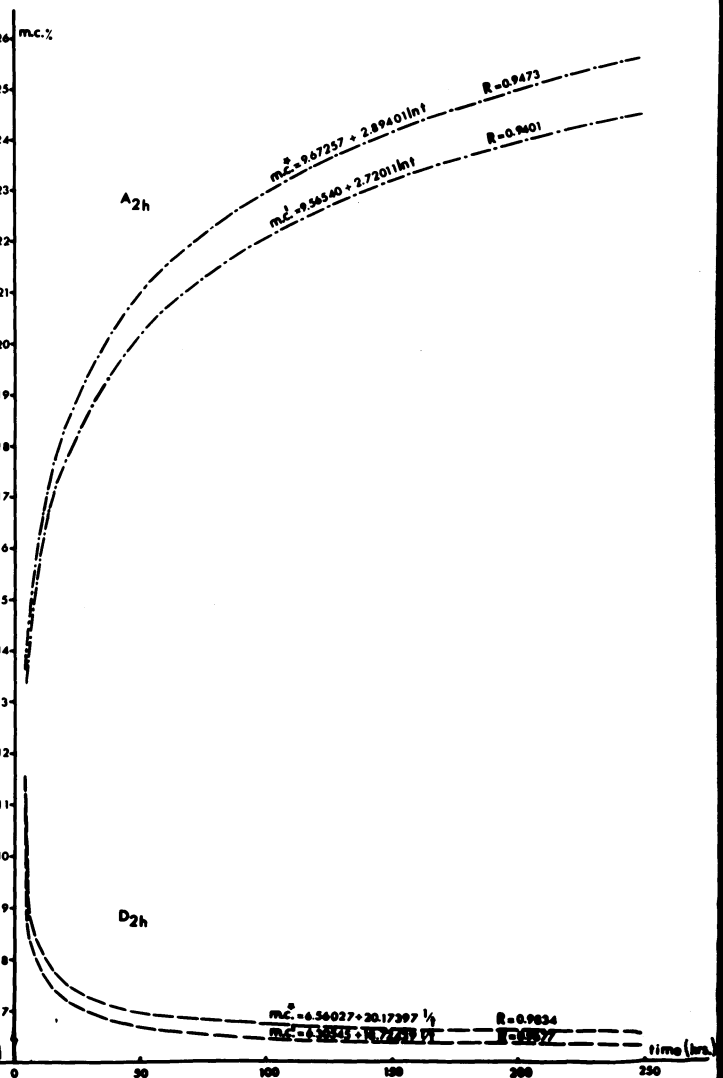
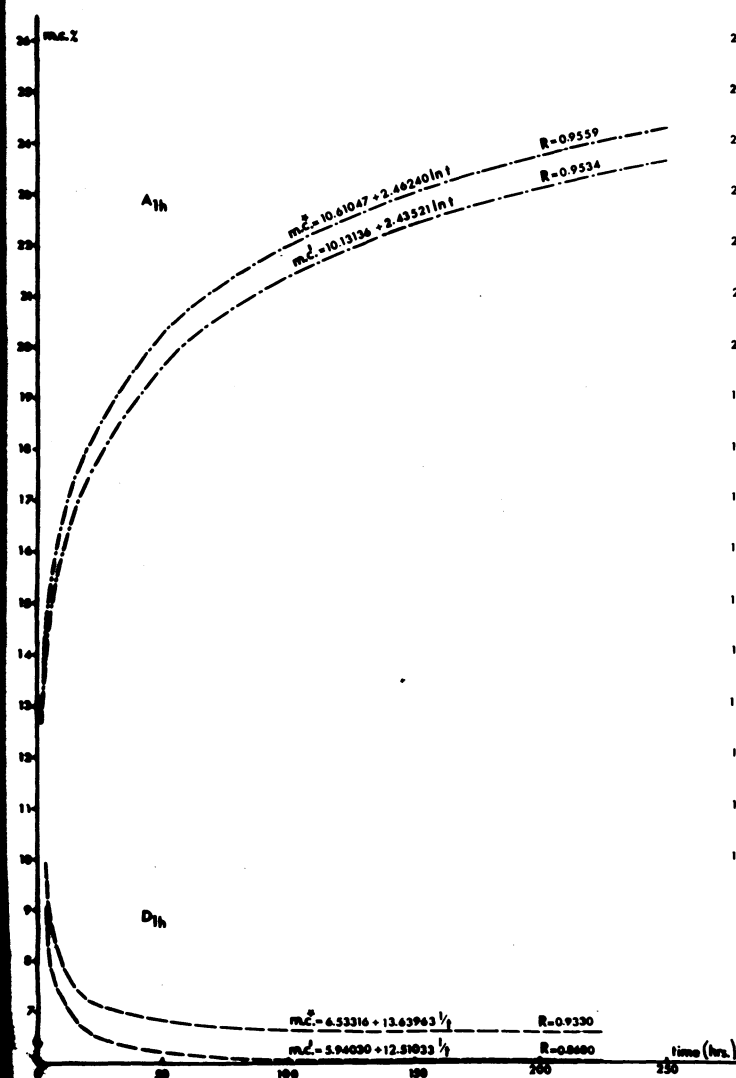
D_{2h} - Desorption second experiment - heavy load

M.C.* - Moisture content of sections in tension (%)

M.C.' - Moisture content of sections in compression (%)

t - Time (hours)

R - Correlation coefficient



the outer tension sections and duration of load application can be found consistently beyond those for moisture content in the outer compression sections and duration of load application in the same co-ordinate system for all experiments at both load levels. This means that the moisture content of the outer sections in compression and tension followed separate curves indicating the differences already discussed. Almost all parts of all curves representing the relationship between moisture content and duration of load application in non-flexed wood were located between those in tension and compression of flexed wood if the same co-ordinate system is used. More detailed analysis of these curves showed that the rate of moisture content change in both flexed and non-flexed wood was high during the first 20 to 25 hours. Then it was gradually decreasing to a lower more or less constant value. The moisture content differences between sections of beams in compression and tension seemed to be independent of duration of load application, moisture gradient, and the direction of moisture transfer. These findings were in good agreement with those of Armstrong (1). Further evaluation of these curves also resulted in a confirmation for the validity of the discussion and theories presented earlier.

On the basis of the preliminary experiments performed by the author another proof can be given for the existence of a moisture content difference for stressed wood in compression and tension.

These experiments were conducted using wood in pure compression, tension, bending, and relaxation under moisture transfer conditions (Figure 2).

(1) Yellow poplar blocks of 1" x 1" x 1-1/4" were used for compression parallel to grain tests. The load used resulted in a compressive stress of 6000 p.s.i., which was applied for one week. The moisture content difference between stressed and stress-free wood was approximately 0.58% with that of the stressed wood being lower (Figure 2e).

(2) Yellow poplar sections of 1/8" x 3/8" x 3-1/2" were used in tension parallel to grain tests. The load used resulted in a tensile stress of 1050 p.s.i., which was applied for one week. The moisture content difference between stressed and stress-free wood was around one percent, with that of the stressed wood being higher (Figure 2a).

(3) Small yellow poplar beams 3/8" x 1/2" x 30" were flexed by a load of 13 lb. in constant humidity for twelve days. The moisture content difference between the outer sections of 1/10" x 3/8" x 1" in size at the center portion of the flexed beams was about half a percent, where the moisture content of the sections in tension being higher (Figure 2c).

(4) Large yellow poplar beams, 1-1/2" x 3" x 7' in size, were loaded with 120 to 175 lb. in desorption condition for one month. The moisture content difference at the center portion of stressed

beams between outer sections of $1/2'' \times 1-1/2'' \times 4''$ was about 0.64% regardless of the magnitude of load levels, with the moisture content of sections in tension being higher (Figure 2b).

(5) Yellow poplar beams of $3/8'' \times 1/2'' \times 13-1/2''$, with an initial load of 50 lb. in relaxation tests were used in adsorption condition for one week. The moisture content difference at the center portion of stressed beams between the outer sections of $1/10'' \times 3/8'' \times 1''$ was about 0.75% with the moisture content of sections in tension being higher (Figure 2a).

The results of these preliminary experiments indicated that the magnitude of moisture content difference due to tensile and compressive stresses was in the same order as found in the main investigation. However, the results of these preliminary experiments can be considered only indications of the phenomenon, since no adequate replications were made.

4/ Creep Deflection as a Function of Duration of Load Application

From the deflection readings observed during each experiment, the actual creep deflections were calculated and recorded as shown in Tables 7 and 8. For illustration, creep deflection data obtained during the second desorption experiment, were plotted against duration of load application, by individual take outs and load levels (Figure 16).

Figure 16. Creep curves for the second desorption experiment.

A - Take out 1

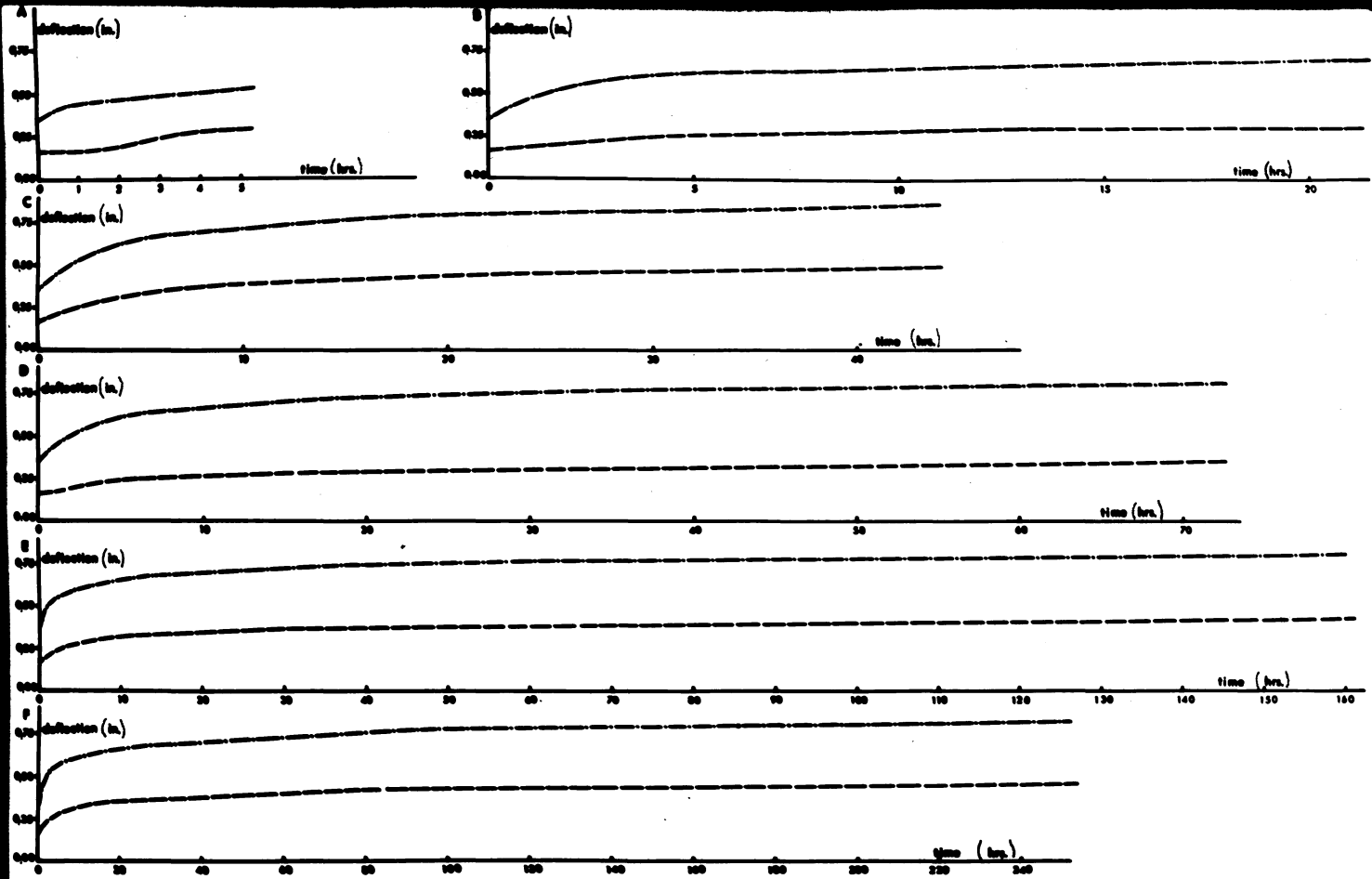
B - Take out 2

C - Take out 3

D - Take out 4

E - Take out 5

F - Take out 6



The maximum total creep deflection occurring under light load was in the neighborhood of 0.4", while beams under heavy load showed a maximum total deflection of approximately 0.8" regardless of the direction of moisture transfer. The ratio between average creep deflections measured at the two load levels was around 1.92. The magnitude of light load level was half of that of heavy load level, and they both were in the elastic range. This means that the expected creep deflection ratio between load levels would be in the vicinity of 2.00. The experimental and expected creep deflection ratio seems to be in close agreement. The small differences between the actual and expected creep deflection ratio was probably due to the fact that the direction of load application with respect to grain direction was not exactly uniform for all specimens, since there was some variation in grain direction among the specimens, which also affected the creep data. The natural variability of wood and a possible small error in the symmetry of load application may, of course, be other reasons for the small variation in creep data and for the slight deviation of actual creep deflection ratio from the expected one. For the evaluation of the relationship between creep deflection and duration of load application, regression analyses were made to select the most representative curves for creep deflection data as a function of time. Since the creep data did not show much variation between the two adsorption and between the two desorption experiments at corresponding load levels, they were combined in these calculations.

A simple logarithmic function (35) was found to fit best for all the data groups as indicated by the high "R" values. Figure 17 shows the derived curves with all necessary information. By excluding the initial creep deflection from the analysis, the relationship between creep deflection and duration of load application would probably show higher significance.

A detailed analysis of these curves indicated that the rate of creep deflection during the first 20-25 hours was high; then it gradually decreased to a more or less constant value. The rate of creep deflection was different for adsorption and desorption in both load levels throughout the experiments. At the initial stage of the experiments the creep deflection rate was higher for desorption specimens; however, at the later stage of the tests the opposite was found to be true.

A further analysis of the creep curves showed that they represented a portion of an idealized creep curve, including the first and part of the second stages. The idealized creep curve and necessary nomenclature are given in Figure 18.

The derived equations obtained by using statistical techniques were found to be similar to those reported by Clauser (10), Young (44) and Kellogg (22). Clauser's creep curve function (10) was proven to be valid up to the inflection point (Figure 18). In light of the similarity of the creep curves, this validity might be considered to apply also here. In other words, in the duration of

Figure 17. Relationship between creep deflection and duration of load application.

- A_{1&2l} - Adsorption first and second experiments - light load
- A_{1&2h} - Adsorption first and second experiments - heavy load
- D_{1&2l} - Desorption first and second experiments - light load
- D_{1&2h} - Desorption first and second experiment - heavy load
- ln - Natural logarithm
- C - Creep deflection in inches
- t - Time in hours
- R - Correlation coefficient

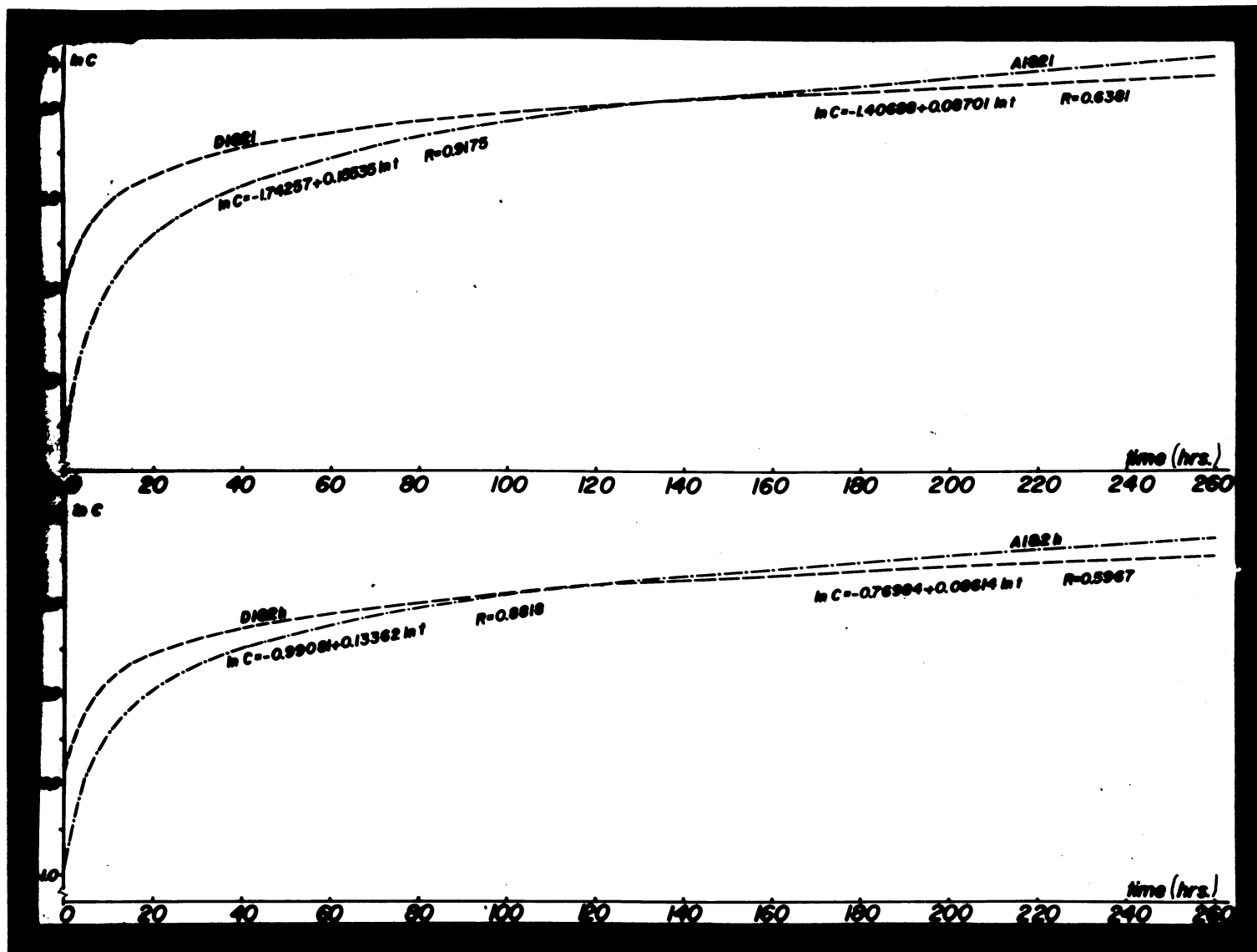
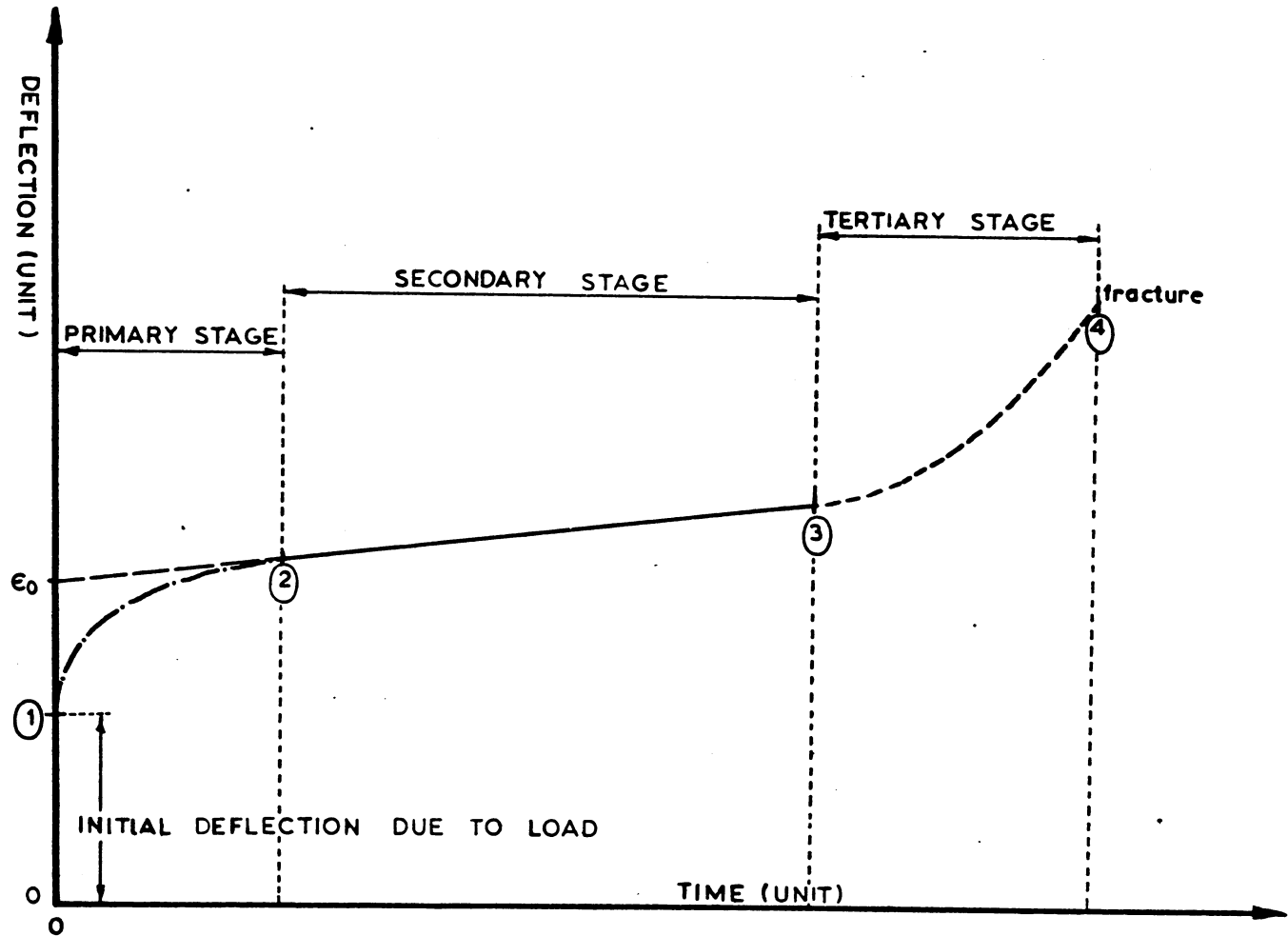


Figure 18. General idealized form of constant-load creep curve. Intercept value of minimum creep rate curve and creep deflection axis.



constant flexural load applications to small yellow poplar beams the creep deflection and time relationship could be represented by the derived function and could be applied up to the inflection point regardless of the direction of moisture transfer conditions (Figure 18).

Armstrong (3) and Kingston (24) had observed that creep deflection and the moisture content change in beams are closely associated. According to the results of this study the observation above appears to be valid, and could also be confirmed by the following theoretical concepts:

In the crystalline regions of cellulose the microfibrils are held together by strong chemical bonds; and, therefore, the strength properties of these regions are quite high. In the amorphous regions of the cellulose the microfibrils are not well oriented resembling a loose structure and, therefore, their strength properties are low in comparison with those of the crystalline regions. According to Barkas (5) a plastic flow takes place in wood under stress even in the elastic range, depending mainly on the moisture content conditions. In flexure this results in a continuously increasing creep deflection associated with moisture content change. Since both load levels were in the elastic range, it was not likely that the resulting stresses could break up the highly complex unit of crystalline regions. Thus, the time dependent deflections might have occurred as the result of the weakness of the amorphous regions. Therefore, the plastic flow

may be resulted from a slippage of the cellulose chains and/or hydrogen bond transfer. This plastic flow as influenced by moisture content change and magnitude of load was expected to increase up to a point where these factors come to equilibrium with the plastic flow. From that point on, however, the plastic flow remains constant. Different load levels in the elastic range, therefore, should not have the same effect on plastic flow. Barkas (5) has shown that the plastic flow in wood is small, due to external stresses within the elastic range. Since the two load levels were in the lower portion of elastic range, the plastic flow created by them can be considered almost the same in both cases. Upon visualizing the creep data, it is evident that the creep deflection was increasing with the increase of magnitude and duration of load, which also can be seen from the creep deflection ratio between load levels. Those findings cannot be explained satisfactorily with the plastic flow, but perhaps by the elastic effect and flow occurred in the flexed beams.

Beams removed from the humidity chamber showed a small set which indicated the presence of plastic flow and elastic flow. The pure elastic effect is recovered by the removal of load. According to Barkas (5) and Bello (7), the elastic flow or retarded elastic deformation is recoverable in time. This could be expected from the following reasoning: When load is removed from beams the newly formed stress and moisture content dependent microfibrillar

structure of the amorphous regions tend to get back to its original orientation, making the beam to return to its more or less original shape. This could be expected since both load levels were within the elastic region. During that process, not all newly formed hydrogen bonds were able to transfer back to their exact original location. This fact results in a small set, that is called irrecoverable creep (16, 17).

This theory may be summarized as follows: Creep deflection occurring in beams under bending is due to elastic and plastic flows in the amorphous regions of the cellulose. The elastic flow is composed of two parts: (1) pure elastic effect and (2) retarded elastic effect. Only that creep deflection which results from total elastic effect is recoverable. Mainly the total elastic effect is responsible for the creep behavior of flexed wooden beams.

5/ Interaction Between Positional Moisture Content and Creep Deflection

Previously it has been shown that duration of load application had a definite effect on positional moisture content and on creep deflection in wood under moisture transfer conditions. According to the experimental data, creep deflection, in addition to time, seems to be closely associated with moisture content change. The possibility of this was also indicated by the discussions of the ultrastructure of wood and thermodynamic concepts of elastic gels.

To analyze the relationship between positional moisture content and creep deflection, calculations were conducted the following ways:

First, the creep deflection was treated as the independent variable, while the moisture content was the dependent variable. By regression methods a third degree polynomial function was found to be most representative for all groups of data as shown in Figures 19 and 20. The "R" values indicated that these curves were highly significant. Since there was a moisture content difference between the extreme sections of beams, due to compressive and tensile stresses, it was possible to construct two curves for each load level in each experiment as shown in Figures 19 and 20.

In the second part of the calculations, moisture content of middle sections was treated as the independent variable while the creep deflection was the dependent variable. (See Figure 4 for the location of middle section.) By regression methods, the relationship between these two variable was analyzed. According to the data available, it was possible to obtain two functions representative for each experiment; that is, one for each load level. The results of these analyses and all necessary information concerning this calculation are shown in Figure 21. The high "R" values indicated that a highly significant relationship existed between the two variables.

In both parts of the calculations, both variables corresponded to duration of load application. In other words, the derived functions

Figure 19. Relationship between moisture content and creep deflection at the extreme sections of beams in desorption by load levels.

D_{1l} - Desorption first experiment - light load

D_{1h} - Desorption first experiment - heavy load

D_{2l} - Desorption second experiment - light load

D_{2h} - Desorption second experiment heavy load

C - Creep deflections in inches

R - Correlation coefficient

M.C.* - Moisture content of sections in tension (%)

M.C.¹ - Moisture content of sections in compression (%)

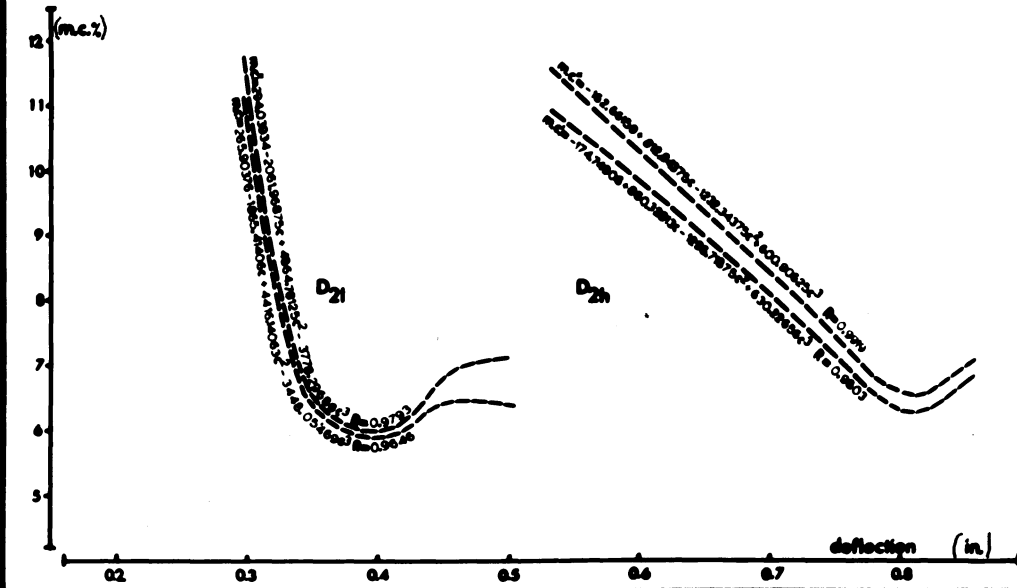
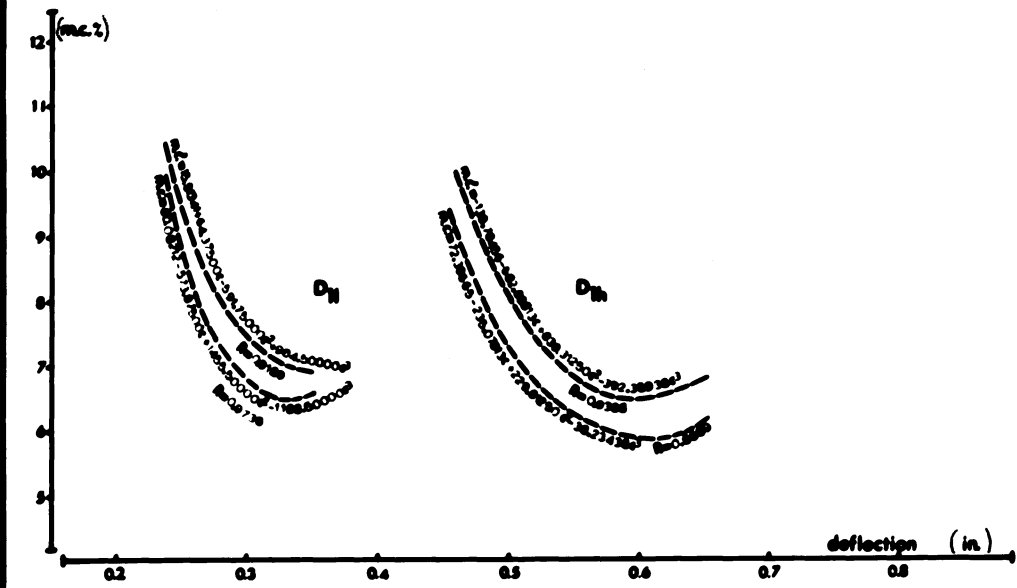


Figure 20. Relationship between moisture content and creep deflection in the extreme sections of beams in adsorption by load levels.

A_{1l} - Adsorption first experiment - light load

A_{1h} - Adsorption first experiment - heavy load

A_{2l} - Adsorption second experiment - light load

A_{2h} - Adsorption second experiment - heavy load

M.C. - Moisture content in outer sections (%)

C - Creep deflection in inches

R - Correlation coefficient

M.C.* - Moisture content of sections in tension (%)

M.C.¹ - Moisture content of section in compression (%)

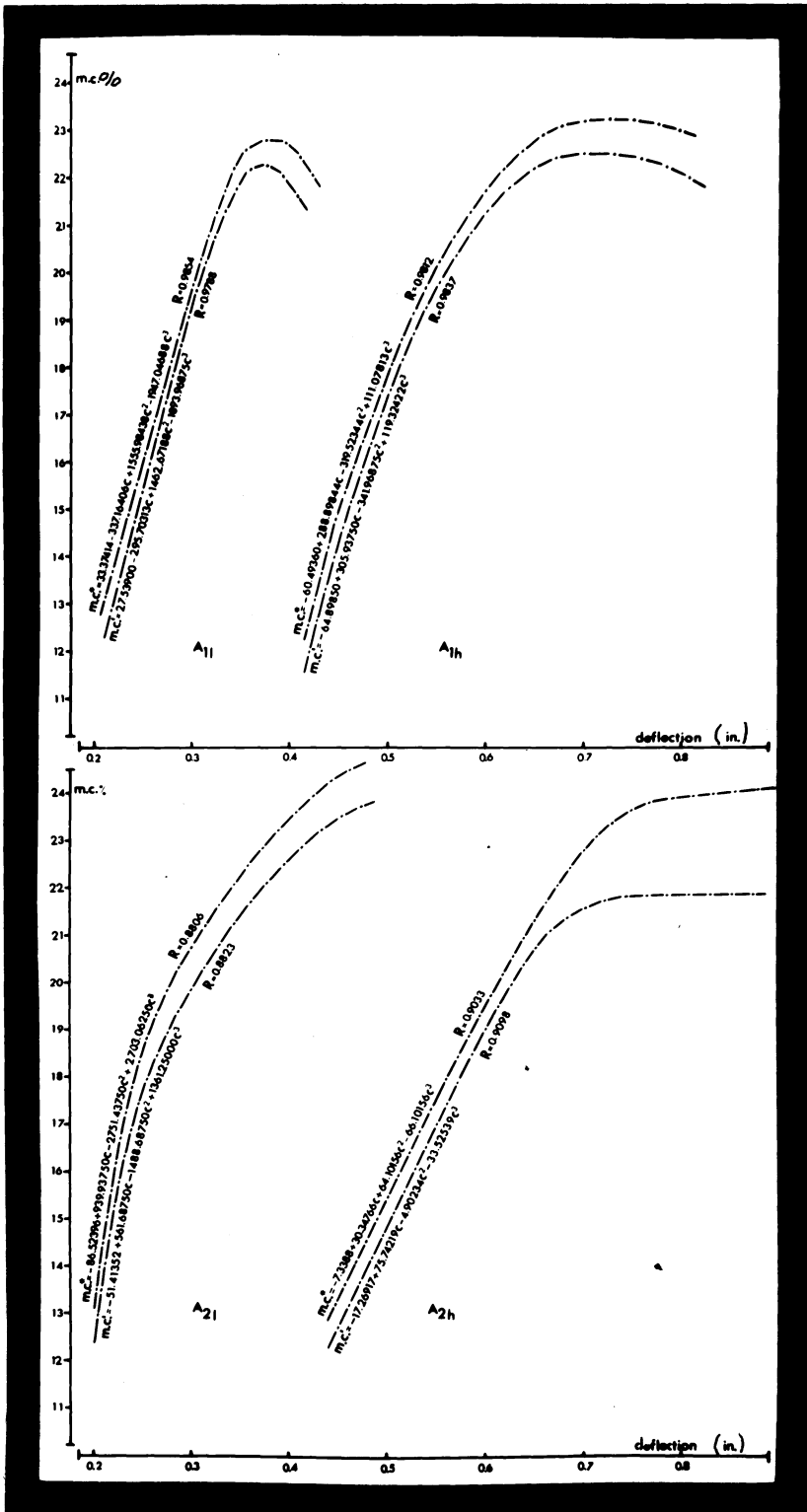


Figure 21. Relationship of creep deflection and moisture content of middle section in stressed beams.

A_1 - Adsorption first experiment

A_2 - Adsorption second experiment

D_1 - Desorption first experiment

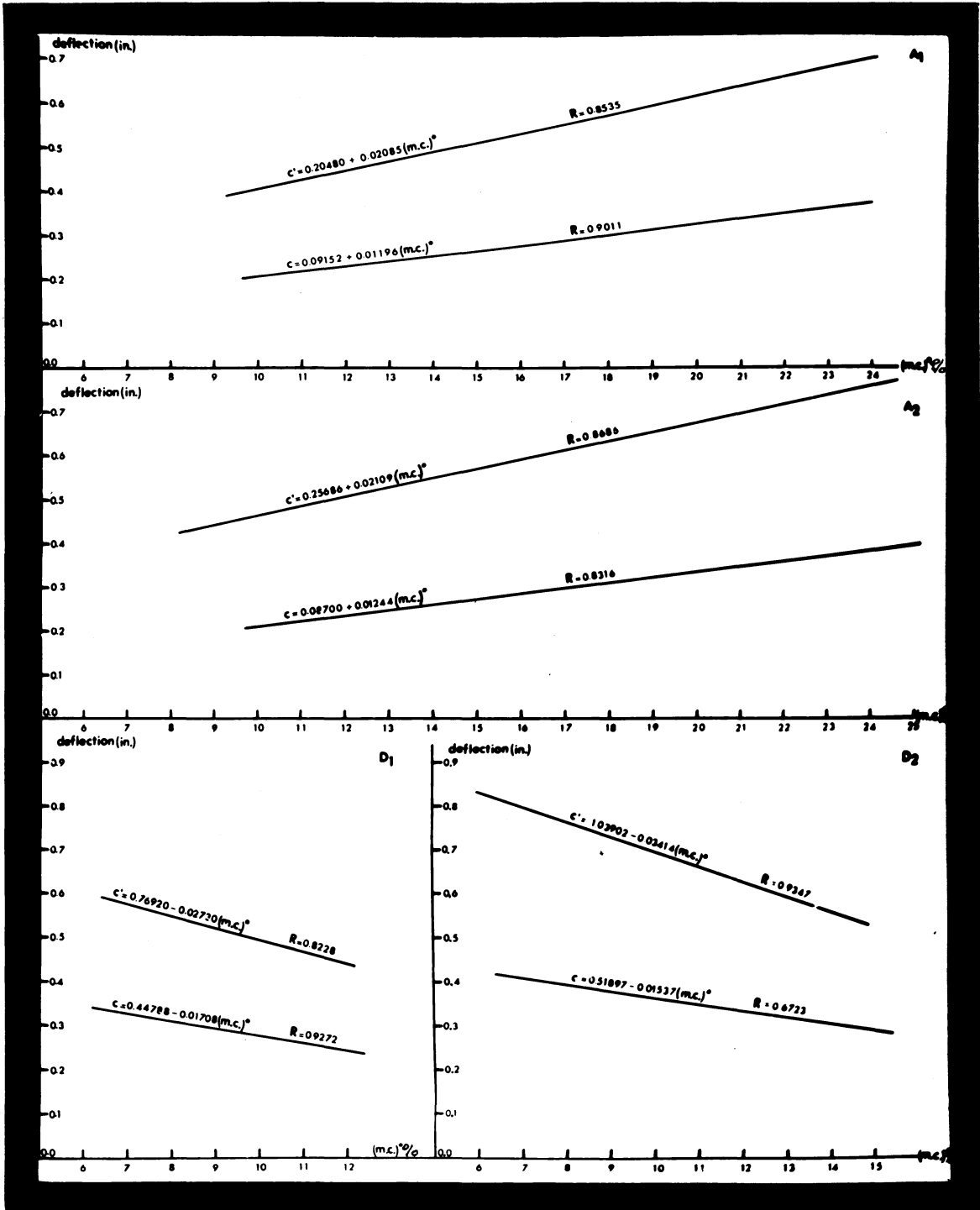
D_2 - Desorption second experiment

C^1 - Creep deflection - heavy load - inches

C - Creep deflection - light load - inches

R - Correlation coefficient

M.C.* - Moisture content of middle sections of beam in %



represent a three dimensional state of relationship among the variables. Since moisture content and creep deflection were changing with the duration of load application in a similar way, it was possible by using the consecutive order of these variables to eliminate the direct appearance of time in the calculations.

The actual strain and moisture distribution in the cross-section of wooden beams under bending usually cannot be represented by a straight line function. According to that, the conclusion can be drawn that there is no linear relationship between moisture content and creep deflection. This assumption can also be supported by the fact that the strength properties of wood due to moisture content variation follow an exponential relationship (40). The results of the above analysis indicated that this hypothesis is only valid for the outer sections, where a polynomial function was found to represent the data satisfactorily. On the other hand, in the middle sections the relationship between creep deflection and moisture content followed a straight line. Both parts of the calculations presented in this chapter showed that the creep deflections increased with changing moisture content and with increase in duration of load application, regardless of the direction of moisture transfer conditions, in good agreement with the theoretical concepts.

CONCLUSIONS

From the results of this investigation, the following conclusions may be drawn:

1. The moisture content on the tension side of flexed wooden beams is significantly higher than that on the compression sides. The magnitude of moisture content differences between the outer sections amounted to approximately one-half of one percent.

2. The moisture content differences due to compressive and tensile stresses in wooden beams were the same regardless of the direction of moisture transfer.

3. The moisture content differences were independent of moisture content levels and moisture gradients.

4. The load levels within the elastic range had almost equal effect on moisture content differences.

5. The highest rates of moisture content changes and moisture gradients occurred in the first 20 to 25 hours of constant load application regardless of the direction of moisture transfer condition.

6. Moisture changes in flexed beams were at a slower rate than those in non-flexed beams.

7. Moisture gradients were higher in flexed beams than those in non-flexed beams, especially during the first stage of the moisture transfer.

8. The total creep deflection and the center moisture content of flexed beams with increasing time in moisture transfer condition had shown a direct relationship.

9. Creep deflection increased with the increase in duration of load application and magnitude of load during moisture adsorption and desorption.

10. Creep deflection under constant load increased with change in moisture content regardless of its direction.

11. Most of the total flexural creep as well as its highest rate occurred in the first 20 to 25 hours during all experiments.

12. Mathematical equations were derived by statistical methods to represent the relationship between important variables in flexed wooden beams.

13. Theoretical explanation of the mechanisms involved in wood while under flexure, can be given on the basis of the ultra-structure of wood and the fundamental thermodynamic concepts of elastic gels.

14. The instantaneous and time dependent elastic effect were responsible for the total creep behavior of flexed beams, which can be supported by the rheological Burger model.

RECOMMENDATIONS

According to the results of this investigation, the following recommendations can be made:

1. In future experiments the use of moisture detectors from which accurate and continuous moisture content observations can be made without the need of cutting samples from the beams and disturbing the surrounding condition is recommended.

2. The use of strain gages for the more accurate determination of the strain distribution in flexed beams and especially in the extreme fibers of the beams should be introduced.

3. In tests where a symmetric loading system is used, the symmetry of load application should be checked more accurately by means of measuring the reaction force at one of the supports using an appropriate load-cell.

4. In tests where wooden supports covered with paint are used, their dimensional changes should be checked more accurately to improve the creep deflection data.

5. Test should be performed on the reversibility of variation in moisture content due to the action of compressive and tensile stresses in flexed beams.

6. Experiments using more load levels in the upper portion of the elastic and the lower portion of the plastic ranges are suggested.

These experiments might show the small, but definite effects of the magnitude of load on the symmetry of moisture distribution in flexed beams during moisture transfer.

7. Experiments should be performed to test the effect of temperature on moisture distribution in flexed beams during moisture transfer.

8. Investigations should be conducted for further explanation of the mechanisms involved in the different effects of compressive and tensile stresses on moisture distribution in wood under bending.

9. Supplementary investigations are suggested to determine the effect of moisture content changes on the properties of wood during stress relaxation.

10. Research is also recommended which will show the correlation of the results for small wooden beams with those for structural members used in construction.

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ABSTRACT
OF
MOISTURE DISTRIBUTION IN WOODEN BEAMS
UNDER CONSTANT BENDING LOAD

by

Tivadar Szabo

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MOISTURE DISTRIBUTION IN WOODEN BEAMS

UNDER CONSTANT BENDING LOAD

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ABSTRACT

Moisture distribution in small yellow poplar beams under two constant load levels was studied in four independent experiments. Beams were subjected to moisture transfer conditions namely; two experiments in adsorption and two experiments in desorption for the duration of ten days each. During this period in each experiment, creep deflection readings were taken frequently, and at six occasions vertical moisture distributions across the grain between the points of load application were determined. Moisture distribution in beams was indicated by five evenly placed positional moisture content measurements. The moisture content determination was based on the oven-drying method.

Experimental results indicated that compressive and tensile stresses influenced the moisture distribution in stressed beams to a different extent. Namely, the moisture content of sections in tension were higher than those in compression, regardless of moisture transfer conditions. This moisture content difference was relatively small and seemed to be independent of moisture content level, moisture gradient and load level. The one half of one percent moisture content

difference, due to compressive and tensile stresses, was found to be significant and its occurrence was explained using theories based on the ultrastructure of wood and thermodynamic concepts of elastic gel materials. Moisture content changes were slower in stressed beams than those in stress-free ones. The rate of moisture content changes was high in the first part of the experiments; then, it gradually decreased to a more or less constant value.

Most of the creep deflection occurred while the major moisture content changes took place in the beams under bending. Then an equilibrium was obtained between moisture content of chamber and specimens and creep deflection stabilized in adsorption and desorption. This phenomenon was in good agreement with theories and results of other investigations. The rate of creep deflection was high during the first stage of the experiments; then, gradually decreased to an almost constant value following a close relationship with the rate of moisture content change.

Using statistical methods the relationships between the following variables were analyzed and discussed: positional moisture content and time, creep deflection and time, creep deflection and positional moisture content. The derived functions representing the relationships were found highly significant.