ABSTRACT

THE DEFLECTION OF COMPOSITE FURNITURE
PANELS UNDER CONSTANT
BENDING STRESS

By

Poo Chow

Experiments have been performed to determine the elastic and inelastic behavior of veneered particleboard and its individual components using a well-known commercial brand particleboard and walnut veneers of various thicknesses. Methods have been developed by which the total maximum creep deflection of a veneered particleboard furniture panel under various moisture contents and loading conditions may be predicted.

Results of analysis of variance for this particular split-plot statistical design indicate that the initial, creep and irrecoverable deflections of the composite panels are highly significantly affected by the independent variables of humidities, shelling ratios, and load levels.

Short term and long term creep test results were compared. The total bending deflection at a rate of creep of 0.0005 inch per day was considered to be the best practical approximation of total maximum bending deflection for

the specimens. The best approximation of total maximum bending and creep deflections as functions of shelling ratio, load level, moisture content and time conditions of the composite panel can be accurately predicted by the use of multivariable least square regression equations with an R^2 value of 0.99 in this study.

The creep deflection and irrecoverable creep increased with increasing humidities from 65 per cent to 90 per cent, increasing loads and decreasing veneer thickness for the specimens. In all cases, the creep deflection was greatest at 90 per cent humidity; also the effect of high humidity on the creep overshadowed the effect of load. The differences of creep deflection are small, between the 30 per cent and 65 per cent humidities but there was a least creep deflection in the particleboard with respect to relative humidity at 65 per cent. Creep deflection was found to be proportionally increased with the increasing of initial deflection for all conditions.

Veneered particleboard had a reduced total bending and creep deflection under all conditions. A large proportion of creep of the panel was reduced by application of 1/36 inch thick veneer on the particleboard surfaces; thereafter the reduction of creep was not proportional to further increasing of the veneer thickness. A veneered particleboard panel with a shelling ratio of 0.5 under sustained loading had a creep result very close to that of

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solid walnut wood. However, from the standpoint of practical and economical purposes, it is unwise and impractical to use a walnut veneer thicker than 1/36 inch on the particleboard core just for the purpose of improving a limited amount of creep property on the composite furniture panel.

It was found that a regular 3/4 inch particleboard is only suitable for use in lightly loaded shelves. One-thirty-sixth inch walnut veneered 3/4 inch particleboard composite can be used for medium duty shelves or bookcases and will meet the creep performance requirement set by the National Kitchen Cabinet Association.

It must be mentioned that the load at the creep limit in bending corresponds to approximately 60 per cent of the load at the proportional limit, or 20-30 per cent of the load at the ultimate bending strength in the static bending test for all specimens of various designs in this experiment.

It is believed that the general behavior shown in this study applies as well to combinations of mat-formed particleboard core with wood veneers of other species, and other types of facing materials.

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I. INTRODUCTION

A. Definition

1. Wood Particleboard

Wood particleboard can be defined as being composed of distinct flakes or particles of wood blended with synthetic resin adhesive, formed into a sheet, consolidated, and the resin cured under heat and pressure or high frequency, the final board being uniform in the plane of the sheet and bonded together by the synthetic resin. The boards may be homogeneous or have surfaces of higher quality or of different texture than the core. Several synthetic resins are used for bonding particleboard; they are urea-formaldehyde, phenol-formaldehyde, and malamine-formaldehyde. Urea-formaldehyde resins are used more than others at the present time.

Particleboard has been manufactured in this country for little more than a decade. It is the newest of the wood panel products, and it is used in virtually any application where a smooth, stable panel product is needed. A major use is as corestock for furniture panels.

The particleboard used in the furniture industry may be divided into two categories according to the method

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of manufacture -- extruded and mat-formed. Panels made by the extrusion process generally are produced and used by the same manufacturer. Mat-formed wood particleboard is sold on the open market for a wide variety of uses in the furniture, building and wood working trades.

2. Composite Furniture Panels

The definition of a composite panel requires that the following criteria be met:

a. It must be a combination of at least two distinct materials with a distinct interface separating the components.

b. It should be created to obtain properties which would not be achieved by any of the components acting alone.

Therefore, a composite furniture panel can be defined as a furniture panel consisting of a number of elements and having properties which would not be achieved by any of the elements acting alone.

A composite furniture panel consisting of wood particleboard core combined with facings of various other materials is a relatively recent addition to the growing family of wood products. Such composite constructions are intended to provide improvement in surface appearance, stiffness and strength, or other physical and mechanical properties. A frequently used example of this type of construction is veneered particleboard, which is found today in a variety of furniture panels. It is also very important to know that the majority of the particleboard used in the

furniture industry is veneered in a three ply construction. Basically there are two different composite constructions in the veneered particleboard furniture panels, namely three ply construction and five ply construction. Whenever the surface smoothness of a particleboard core is not adequate enough to prevent the "show-through" problem in a polished veneer surface, a five ply construction is often used.

B. Statement of Problems

The development of the particleboard industry promised an ideal core material for veneered panels. In general, the lumber core furniture panel always requires a five ply construction. It is relatively expensive to manufacture the lumber core furniture panel in the furniture plant; therefore the furniture industry is taking advantage of the economics offered by the extensive use of particleboard. Frequently, particleboard is considered as a direct substitute for lumber core material.

In the comparison of performance on the basis of bending strength properties between these two core materials, unfortunately, the particleboard core happens to be inferior to lumber core along the grain direction in bending strength. The details of these problems are described as follows:

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The use of particleboard as core material in furniture panels often results in excessive bending deformation when these panels are exposed to sustained loading. Particleboard is, therefore, often rejected in favor of lumber core board in applications where bending stresses are considerable and/or of long duration.

Furniture panels are generally of a composite sandwich design. Each component contributes to the behavior of the panel according to its individual properties, its relative thickness, and its location in the panel. Short term deflections of such panels can readily be calculated, assuming elastic responses. Long term deflections, however, are in part due to creep and cannot be determined by elastic theory. The difficulties are compounded by the strong influence of changing moisture content on the creep deflection of such panels. The permanent deflection or sagging problems are most important when panels are used in a horizontal position like table tops or shelves, which will deflect and sag under a constantly applied load, such as books, merchandise, etc. To date, there is no information available on the creep behavior of composite furniture panels under practical constant load. The only bending deflection information which can be collected from the particleboard manufacturers today is limited to the elastic deflection of the particleboard core panel.

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Due to the economic reason and the shortage of hardwood timber in this country, the amount of fancy defect-free veneers that can be used in furniture panels is limited. Extremely thin veneers, only one thirty-sixth of an inch thick, are generally used in the particleboard furniture panels by the furniture industry. This adequately serves the purpose of improving surface appearance of the particleboard furniture panel, but the excessive bending deflection which has occurred to the veneered particleboard panel might be caused by the use of this extremely thin veneers.

In fact, permanent deflection or sagging does happen in spite of no load being imposed on the table tops or shelves in a horizontal position (34). The only explanation for this peculiar case is that the panels might deflect and sag under their own weight. As we can see, the actual weight of a table top or shelf alone is relatively low and its loads are all within the elastic limit of the composite structure. First of all, this creates a question -- Whether sagging or permanent deflection is caused solely by practical external load on the furniture panel? The second question might be -- Are the sagging and permanent deflection partly caused by the unbalanced internal stresses which occur during the swelling and shrinkage in a fluctuating moisture condition?

Due to the economic reason and the shortage of hardwood timber in this country, the amount of fancy defect-free veneers that can be used in furniture panels is limited. Extremely thin veneers, only one thirty-sixth of an inch thick, are generally used in the particleboard furniture panels by the furniture industry. This adequately serves the purpose of improving surface appearance of the particleboard furniture panel, but the excessive bending deflection which has occurred to the veneered particleboard panel might be caused by the use of this extremely thin veneers.

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C. Objectives

The primary objectives of this study are:

a. To determine the elastic and inelastic behavior of veneered particleboard and its individual components using a well known commercial brand of particleboard and walnut veneers of various thicknesses.

b. To develop a method by which the total maximum creep deflection of a veneered particleboard furniture panel under various moisture contents and loading conditions may be predicted.

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II. VISCOELASTIC BEHAVIOR OF WOOD AND WOOD-BASED MATERIALS

A. Definition

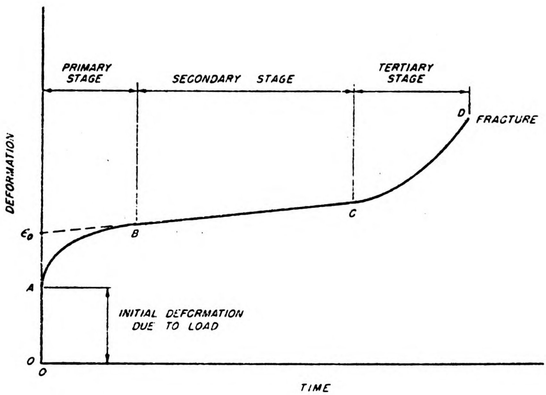
The phenomenon of material deforming under constant load is called creep and the science of such deformation is known as rheology (29). It is evident that wood and wood particleboard possess rheological properties which cause their strength to be a function of load duration. The creep behavior of wood, like most structural materials, deforms instantly under load in relation to the stress imposed and continues to deform as the load is maintained (9).

A typical deformation-time relationship for wood under constant load is shown in Figure 1(a), (b).

The elastic (instantaneous) deformation is largely strain, conforming to Hook's law, and the increase in strain that occurs with time under load is termed plastic deformation. Plastic deformation is partly recoverable with time and partly irrecoverable. The recoverable part is commonly called retarded elastic deflection and the irrecoverable part is called flow (37).

Figure 1.--(a) A typical deformation-time relationship for wood under constant load (9)

(b) A typical cycle of intermittent loading for wood (37)



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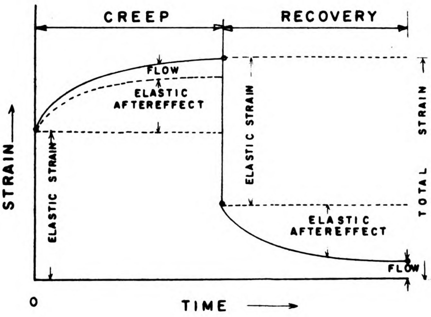

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The behavior of wood materials under stress reflects the combination of solid-like and liquid-like characteristics. Materials exhibiting this kind of behavior are known as "viscoelastic materials." In a viscoelastic material both stress and time anomalies could exist. Where the stress anomalies are absent, the material is called "linearily viscoelastic." The irrecoverable deformation in a viscoelastic material is similar to the flow of liquid under stress; therefore this component of total deformation in wood will be referred to as "flow" (37).

B. Analogue on Viscoelastic Behavior

A physical concept of viscoelastic behavior can be obtained from a mechanical model consisting of series and/ or parallel combinations of springs and dashpots (26), such as shown in Figure 2. The response of a single model to a constant load or stress is indicated by Figure 2(a), (b). In this creep model where A represents the purely elastic deflection due to the spring element E_1, and B represents creep deflection due to the retarded elastic spring element of E_2 and dashpot N_2, C represents the creep deflection due to the flow element of dashpot N_3. This model can be used to describe the behavior of wood and wood particleboard in creep. The retarded elastic deflection is that type of deflection which requires time to develop and is completely recovered with time. The flow part of the creep deflection

Figure 2.--Creep models used to describe the viscoelastic behavior of wood (26)

(a) Single Dashpot Creep Model

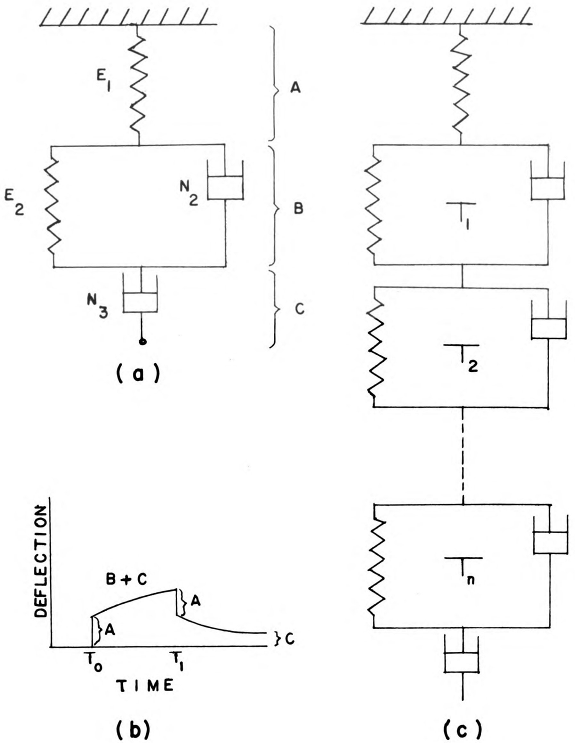
A = Elastic deflection due to the spring element E_1

B = Creep deflection due to the retarded elastic spring element of E_2 and dashpot N_2

C = Creep deflection due to the flow element of N_3

(b) Deflection-Time relationship of the creep model under constant load (T_o-T_1) and after load removal at time T_1

(c) Creep model with a series of connected retarded elastic elements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is also that type of deflection which requires time to develop, but it is irrecoverable.

An equation describing creep under a constant load or stress of a linear viscoelastic material may be expressed as:

$$Y(t) = P\left[\frac{1}{E_1} + \frac{1-e^{-t/\tau\sigma}}{E_2} + \frac{t}{N_3}\right]$$

where

$Y(t)$ = The deflection of the creep model shown in Figure 2(a), (b)

E_1 and E_2 = Spring constants in mechanisms A and B respectively - force/length

N_2 and N_3 = Viscosities associated with the dashpots of mechanisms - force/velocity

$\tau\sigma$ = N_2/E_2 (Retardation time constant)

In order to construct an analogue model that will quantitatively behave as a real material, we can illustrate a widely used approach. The model in Figure 2(c) shows a series of connected retarded elastic elements. It is often convenient to let the number of retarded elements go to infinity. The deflection of this system due to a constant load P can be written as:

$$Y(t) = P\left[\frac{1}{E} + \int_{-\infty}^{+\infty} L(t)(1-e^{-t/\tau})\, d\ln_\tau + \frac{t}{N}\right],$$

where L(t) is called the spectrum of retardation times. This equation may account for all of the three types of def

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deflections in wood and wood particleboard explained before, provided that the material exhibits linear flow.

In addition to the use of mechanical analogies (models composed of springs and dashpots), the viscoelastic behavior of a material may also be represented by direct graphical display of test results, by fitting the data to some suitable mathematical expression. It should be understood that the mechanical models do serve the purpose of demonstrating the viscoelastic behavior of materials, and they also yield a mathematical representation which is often very convenient. However, there is the danger of overextending the analogy and assigning the role of springs and dashpots to individual components or elements of wood and particleboard, which is an unjustified and misleading simplification (34).

C. Rheology Relation to Moisture Content in Wood and Wood Based Materials

1. Wood

Moisture in wood acts as a plasticizer, and increases in moisture content will usually lead to increases in creep.

The major components of wood are cellulose and other long chain polysaccharides (65-75 per cent) and lignin (31). Cellulose in wood exists in the form of highly crystalline areas with intermittant amorphous regions.

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In these amorphous regions, there is no cross linkage between the cellulose molecules. These regions can also be called "viscous" regions (19). The crystalline regions in the cellulose microfibrils are thought of as being perfectly elastic.

In theory, there are two components of bending deflection developed during sustained loading on the wood, namely elastic and plastic components (24). The elastic components occur in the elastic cellulose chains and the plastic components occur in amorphous regions or "viscous" regions. Thus it is possible that the amorphous regions in the cellulose microfibrils must be responsible for part of the creep deflection of the structure of the cell wall in wood.

Cellulose has been considered as a hydrogen-bonded structure (4). At high humidity conditions, water may form a bridge between two cellulose chains. Such a link will be weaker than one not involving water. The large amount of water reduces the strength and stiffness of wood; thus it is probable that hydrogen bonds play an important part in producing some of the creep deflection in wood.

Lignin in wood is generally believed to be viscous in nature, with cross links between its molecules. This leads to the belief that lignin must also be responsible for part of the creep deflection under sustained loading in wood.

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In bending, total deflection and creep rate have been found to increase with increasing moisture content. Cyclic changes lead to large increases in beam deflection during desorption and recovery of deflection during the first or second adsorption period, depending on initial moisture content (1, 7). As bending stresses become greater and moisture content changes smaller, recovery during adsorption may be replaced by a reduction in creep rate (29). Armstrong and Kingston (2) found that creep deflection in solid wood increased significantly during both adsorption and desorption. Schniewind (18) has shown that cyclic changes in environmental conditions can shorten considerably the creep-rupture life of Douglas-fir specimens. Daily variation in temperature and relative humidity would affect only the surface layers and hence only a small proportion of the total wood volume. The change in internal moisture content in large beams may therefore become negligibly small and thus lead to only minor reduction in creep-rupture life.

Armstrong and Kinston (3) noted that small beams which were loaded green and kept green during creep tests and those which were loaded dry and kept dry showed about the same relative creep, but this was doubled when initially green beams were allowed to dry under load.

The prevalent view regarding the mechanism of the sorption effect on creep is that sorption involves the

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temporary breaking and reforming of hydrogen bonds. Constant loads in creep experiments produce a bias in the reforming of the bonds, resulting in new positions and changes in shape. This has been discussed in detail by G. J. Gibson (11).

2. Hardboard

Suchsland (33) studied the swelling stresses and deformations in hardboard. Suchsland stated that the causes of stresses in a hardboard have two sources. First, the stresses result from external loads. Second, the stresses might result from restrained expansion or contraction due to hygroscopic moisture content changes. This swelling stress can be considered as an internal stress which may cause permanent deformation in hardboard with an unbalanced moisture content or under restrained condition in the panel.

At high humidity conditions, a hardboard panel would expand stress free and without distortion, if the panel element was applied without any lateral restraint. Any partial restraint would give rise to swelling stress under certain conditions, and these swelling stresses would be accompanied by transverse bending deformation. In restrained expansion of hardboard, compressive stresses are associated with expansion and increase with increasing moisture content (33).

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Moslemi (22) studied the effect of moisture content, board type, and load level on the creep and recovery in both wet and dry process hardboard. The measurement of total creep over a two hour period revealed that deflection at the low moisture level exceeded that of intermediate moisture. The greatest amount of creep was produced at the high moisture level. In dynamic experiments (21), Moslemi found that the modulus decreased with increasing moisture content, while the loss of modulus increased.

Sauer and Haygreen (28) indicated that the flexural creep behavior of wet and dry process hardboard was greatly influenced by sorption. Adsorption produced far greater creep than that which developed during constant or desorption conditions. Increases in temperature and stress level during constant or changing sorption conditions produced an increase in creep. Dry process hardboard exhibited greater creep than wet process hardboard, except under test conditions of low stress and moisture conditions.

3. Particleboard

In 1960, Liiri (20) found that bending strength and tensile strength parallel and perpendicular to the three-layer particleboard surface were reduced approximately 50 per cent by increasing moisture content from 10 to 20 per cent. Maximum levels were achieved at about 10 per cent moisture content for all strength properties considered,

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with reduced strengths at lower moisture content levels. Modulus of elasticity was not considered. Bryan and Schniewind (6) tested wood particleboard and discovered that with the exception of desorption from very high moisture content, the effect of sorption is to increase the relative creep level beyond that which is obtained during constant moisture content conditions. Subjecting material to conditions causing alternating shrinking and swelling results in significant reductions of strength, stiffness, and specific gravity.

Hann (12) reported that at high relative humidity, two major factors and the interactions of these factors are believed to have caused the decrease in strength in the particleboard.

a. Springback.--When a particleboard is exposed to high humidity, the swelling that takes place is not only the normal swelling of the wood but also springback. Springback can be defined as recovery from the compression set that is induced during the pressing operation. The springback that occurred in the specimens subjected to the high humidity very likely caused a reduction in strength because of lowering of the board density and breaking some of the bonds between the particles.

b. Deterioration of the binder.--When urea-formaldehyde resin is exposed to high humidity, it gradually deteriorates (12). In other words, the holding power of

the glue bond decreases with increasing time, due to the nondurable nature of this type of adhesive in the interior type of particleboard.

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III. EXPERIMENTAL PROCEDURES AND DESIGN

A. Preparation of Specimens

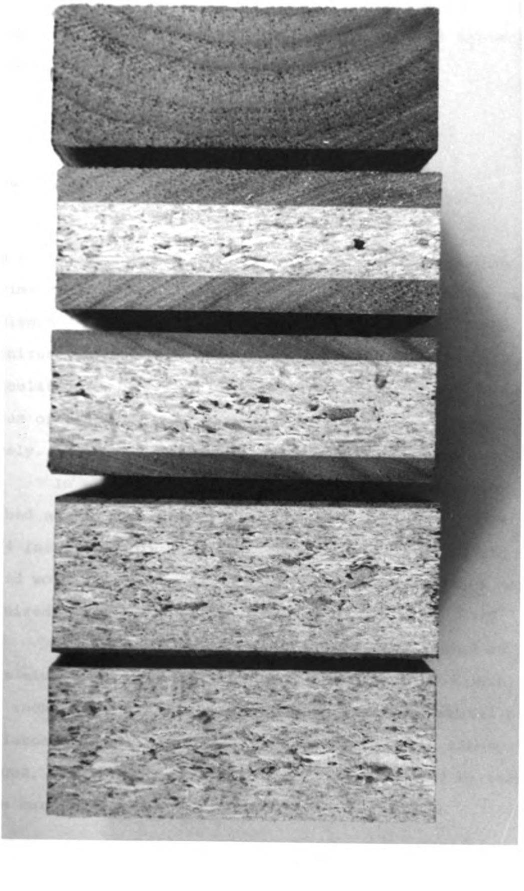
As indicated in the "objectives" of Chapter I, the important objectives of this study were to determine the creep behavior of veneered particleboard and its individual components using a commercial particleboard and walnut veneers of various thicknesses and to predict the total maximum creep deflection of a veneered particleboard furniture panel under various moisture contents and loading conditions. In order to accomplish this task, it was decided to carry out a reasonable number of short term creep experiments on the variables of various designs, load levels and moisture contents of furniture panels.

The total thickness of all individual specimens of various designs was maintained at approximately 3/4 inch, for this thickness was the common thickness of standard commercial shelves or table tops. To investigate the influence of various face veneer thickness on the creep behavior of the sandwich, the number of the sandwich structures was divided into five different groups (Figure 3). For convenience, these groups were simply distinguished by the

Figure 3.--Designs of sandwich structure (end view) (photo 1)

From top to bottom:

3/4 inch solid walnut, 3/16 inch walnut veneered particleboard, 1/8 inch walnut veneered particleboard, 1/36 inch walnut veneered particleboard, and 3/4 inch particleboard



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shelling ratio. In this experiment, a shelling ratio may be defined as the ratio of the thickness of face veneers of a sandwich to the total thickness of a sandwich.

$$\text{Shelling ratio} = \frac{2t_f}{2t_f + t_c},$$

in which t_f = single face veneer thickness

t_c = particleboard core thickness.

The detail descriptions of the sandwich design for this experiment are listed in Table 1. A 1/36 inch veneered particleboard furniture panel is most commonly used by the furniture industry at the present time. The shelling ratio calculated for the five specimen structures were in the order of 0.000, 0.074, 0.333, 0.500, and 1.000, respectively.

In order to provide the kinds of specimens described above, three thicknesses of particleboard panels (3/4 inch, 1/2 inch, 3/8 inch) and four thicknesses of solid wood (3/4 inch, 3/16 inch, 1/8 inch, 1/36 inch) were required.

All the test specimens of particleboard used on this study were prepared from 4 x 8 foot size, 3/8 inch, 1/2 inch, 3/4 inch thicknesses, three-layer commercial particleboard manufactured by Dura-flake Company in Albany, Oregon. Their products have been widely accepted by furniture manufacturers. The surface of a three-layer

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Table 1.--Sandwich design

	Description	Total Thickness*	Shelling Ratio**
(1)	3/4 inch Particleboard	0.750 inch	0.000
(2)***	1/36 Walnut + 3/4 inch Particleboard + 1/36 inch Walnut	0.805 inch	0.074
(3)	1/8 inch Walnut + 1/2 inch Particleboard + 1/8 inch Walnut	0.750 inch	0.333
(4)	3/16 inch Walnut + 3/8 inch Particleboard + 3/16 inch Walnut	0.750 inch	0.500
(5)	3/4 inch Solid Walnut	0.750 inch	1.000

*Glue line thickness is included.

**Shelling ratio = $\frac{2t_f}{2t_f + t_c}$

(t_f = single face veneer thickness)
(t_c = particleboard core thickness)

***Most commonly manufactured by the furniture industry at the present time.

particleboard is made up of very small wood particles. From the standpoint of surface smoothness, a three-layer particleboard core does not require crossband veneers in the veneering process. Face veneers are generally applied directly to the particleboard to produce a three ply constructed panel. Therefore, a five ply construction which has been used in lumber core was unnecesssary on the three-

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layer particleboard core material. Figure 4 shows the cutting diagram for the 4 x 8 foot particleboard panels.

Walnut wood veneer has been extensively veneered on the particleboard core panel by furniture manufacturing firms because of its noble appearance, high strength, excellent machinability and durability. It was decided to use this particular wood species as facing material for the particleboard core panels. One-eighth inch, 3/16 inch, 3/4 inch thicknesses of defect free and straight-grained walnut wood were prepared from 1 inch solid walnut lumbers which had been purchased from Johnson Lumber Company in Charlotte, Michigan. One-thirty-sixth inch quarter cut walnut veneers were also purhcased for use in specimens preparation.

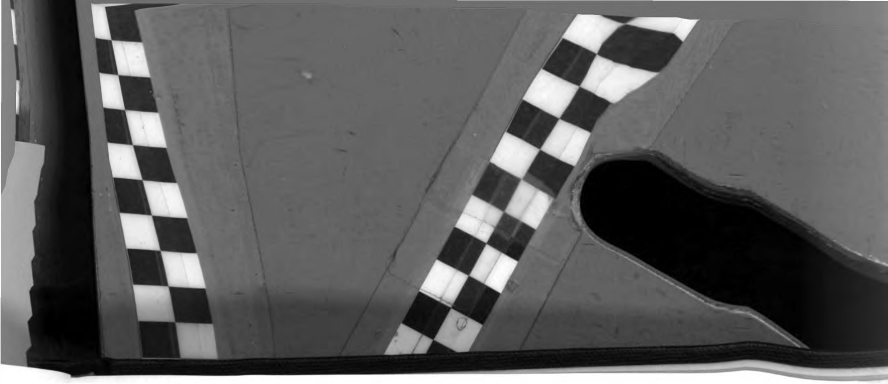
The composite sandwich panels were matched and laminated in a plywood hot press at the laboratory. Urea-formaldehyde liquid resin (Perkin L-100) and catalyst (Perkin S-120) were used as bonding agents. The pieces were pressed at 300°F under a pressure of 150 psi for two minutes. Following the application of wood veneer on the surface of the particleboard core, the panels were trimmed to a specimen dimension of 2 inches x 20 inches (Figure 5).

Equilibrium moisture content condition in the interior of buildings in the United States induces moisture content values from 4 per cent to 14.0 per cent in interior wood trim and furniture (25). It is nearly equivalent to

[illegible]

[illegible] ticleboard only)

Figure 4.--Cutting diagram of particleboard panels (for 3/4 inch, 1/2 inch, and 3/8 inch thicknesses)



96 inches

Panel 1:

OV-1	S&C-1	OV-3	S&C-3	48 inches
OV-2	S&C-2	OV-4	S&C-4	

Panel 2:

S&C-5	OV-5	S&C-7	OV-7	48 inches
S&C-6	OV-6	S&C-8	OV-8	

OV = Overlay Panel. (For Static and Creep Test)

S&C = Static Test and Creep Test Panel. (Particleboard only)

Figure 5.--Specimens preparation (all the panels obtained from Figure 4)

|←→| 2 inches (a) OV-1,2 or S&C-1,2

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C

↕ 20"

(b) OV-3,4 or S&C-3,4

19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C

↕ 20"

(c) OV-5,6 or S&C5,6

37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C

↕ 20"

(d) OV-7,8 or S&C-7,8

55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C

↕ 20"

S=Specimen for Static Test.
C=Specimen for Creep Test.
OV=Overlay Panel.
S&C=Static and Creep Test for Particleboard only.
Humidity Condition and Stress Level are randomly assigned to the individual specimen.

the conditions of relative humidity ranging from 30 per cent to 90 per cent. In order to cover all possible conditions, specimens were conditioned in the humidity controlled rooms for at least four weeks before they were subject to test. The relative humidities of these conditioned rooms were 30 per cent, 65 per cent and 90 per cent, respectively. A constant dry bulb temperature of 68°F was maintained for all conditions.

B. Tests

A series of preliminary static and creep tests was conducted under a 65 per cent relative humidity condition. The results of static tests for particleboard core alone were used to determine the variability of the particleboard of various thicknesses. These preliminary bending test results are listed in Table 2. Among the particleboard panels of three thicknesses (3/8 inch, 1/2 inch, 3/4 inch), the average modulus of elasticity varied from 515,000 psi to 575,000 psi, and the average board density ranged from 44.00 lbs/cu. ft. to 46.00 lbs/cu. ft. The variations of the stiffness values were relatively small among these three thicknesses of board. It could be assumed that the stiffness property of the particleboards used in this experiment was the same, regardless of the particleboard thickness.

Table 2.--Preliminary bending test result of particleboard*

		Particleboard 3/8 inch	Particleboard 1/2 inch	Particleboard 3/4 inch
Density (lbs/cu.ft.)	Average	46.00	44.00	45.00
	Standard Deviation	2.00	2.00	1.00
M.O.R. (psi)	Average	3100	2700	3500
	Standard Deviation	300	400	300
M.O.E. (psi)	Average	535,000	515,000	575,000
	Standard Deviation	60,000	57,000	50,000

*Each average value was obtained from twenty tests.

The preliminary creep test results indicated that 3/16 inch walnut veneered particleboard and 3/4 inch solid walnut wood did not creep at loads less than 10 pounds using an 18 inch span on a 2 inch x 20 inch specimen. In addition to the above tests, the creep tests were also carried out on a 3/4 inch particleboard and a 1/28 inch walnut veneered particleboard with a load equivalent to 10 per cent of ultimate bending load. Both of the specimens indicated the following general creep behavior:

a. Creep deflections are related to the time.

b. Creep deflection or relative creep is increased at a decreasing rate as time is increased.

For the actual experiment, two basic sets of specimens were prepared. The first set of specimens was for the static test and the second set of specimens was for the creep test.

1. Static Bending Test

In order to specify the proper load level of bending in creep experimentation, the static strength of the materials had to be determined. Specimens 2 inches x 20 inches were simply supported with an 18 inch span length and were tested with an Instron testing machine (Figure 6). Except for the width of the specimens, the tests were conducted in accordance with the procedure set forth in ASTM 1037-64.

Specimens at 12 replications of each panel type were statistically tested at various moisture contents to determine the proportional limit, the average ultimate strength (modulus of rupture), the stiffness (modulus of elasticity), modulus of rigidity, and shear deflection.

2. Creep Test

A specially designed creep test device was made so that two beams could be tested at the same time while the constant load was applied by means of weights coupled to the specimens through a lever-arm system (Figure 7). The

Figure 6.--The static bending test (Instron testing machine)
(photo 2)

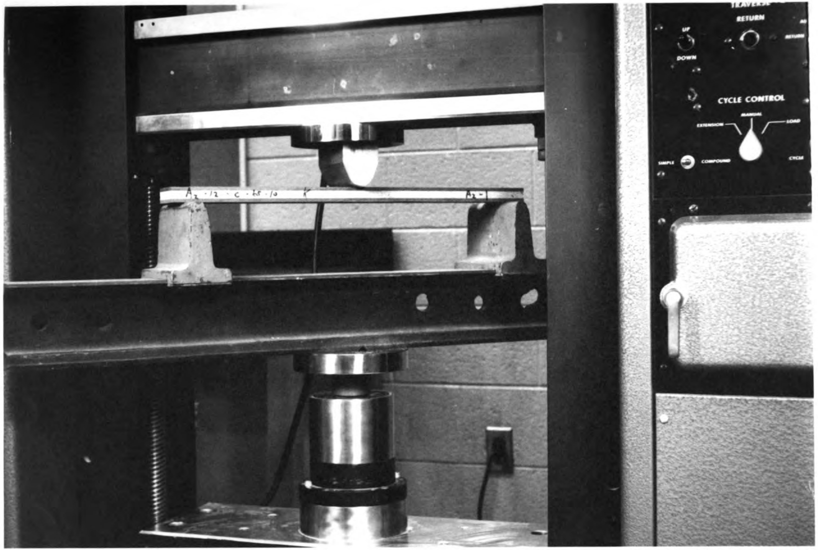

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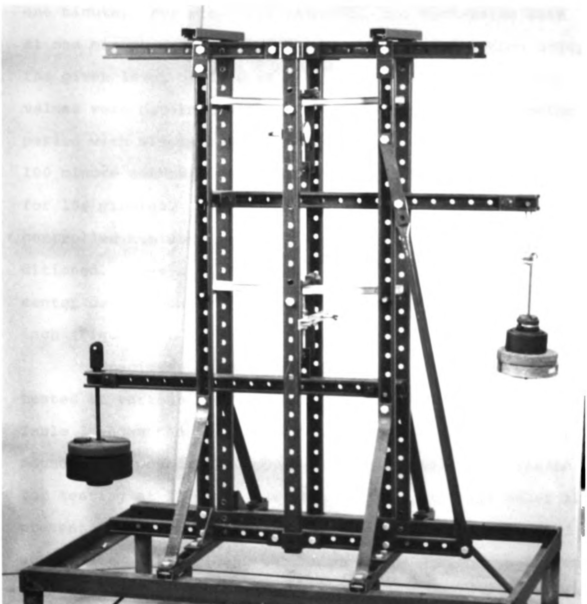
Figure 7.--The creep testing set-up (photo 3)



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shortest time for which deflection data were available was one minute. For practical purposes, the deflection data at one minute were defined as the elastic deflection under the given level of load in this creep experiment. Creep values were determined for a 100 minute sustained loading period with simply supported center-loaded beams. After a 100 minute constant load, specimens were allowed to recover for 100 minutes. All of the tests were performed in the controlled humidity rooms in which the materials had conditioned. Ames dial indicators were used to detect the center deflection of the specimens to the nearest 0.001 inch (Figure 8).

Specimens at two replications of each type were tested at various relative humidities and load levels. Table 3 shows the load levels as 10 pounds, 30 pounds, 60 pounds, 120 pounds, 200 pounds, respectively. The reason for testing at 10 pounds as minimum load was that under the present creep testing set up a load below 10 pounds would not create a significant amount of creep deflection for the 3/16 inch walnut veneered particleboard and 3/4 inch solid walnut beam specimens in the size of 2 inches x 20 inches with an 18 inch span length. Constant loads of 120 pounds and 200 pounds were not used on the 3/4 inch particleboard and 1/36 inch walnut veneered particleboard specimens because these loads would have caused bending failure. The creep deflections of the five kinds of specimens with

Figure 8.--A close-up view of creep testing (photo 4)

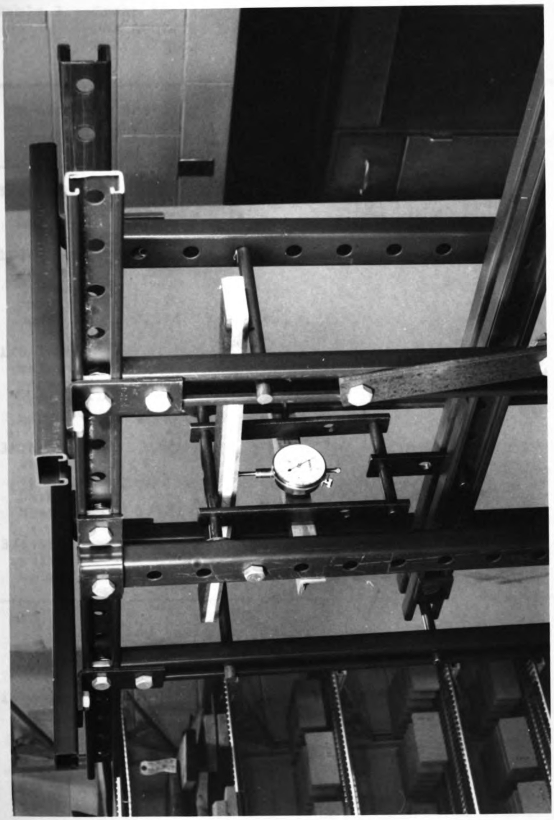

photo 4)

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Table 3.--Creep test (tested at relative humidities of 30 per cent, 65 per cent, 90 per cent, respectively)

Products	Shelling Ratio	Constant Load				
		10 Pounds	30 Pounds	60 Pounds	120 Pounds	200 Pounds
3/4 inch particleboard	0.000	X	X	X	0	0
1/36 inch walnut veneered particleboard	0.074	X	X	X	0	0
1/8 inch walnut veneered particleboard	0.333	X	X	X	X	X
3/16 inch walnut veneered particleboard	0.500	X	X	X	X	X
3/4 inch solid walnut	1.000	X	X	X	X	X

$$\text{Shelling Ratio} = \frac{2t_f}{2t_f + t_c}$$

in which t_f = single face veneer thickness

t_c = particleboard core thickness

X -- tested

0 -- no test

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various designs were measured at various relative humidities under the loads of 10 pounds, 30 pounds, 60 pounds, respectively, for comparison purposes. These three load levels are expressed in terms of percentage of the stresses at proportional limit and ultimate bending strength of the specimens at three different humidity conditions in Table 4. These three load levels were considered as low stressed practical loading conditions which could happen to shelves or table tops in actual service. One hundred twenty pounds and 200 pounds were considered as high stressed load. Ten pounds is typical of the load in service of a lightly loaded bookshelf, being equivalent to 14 pounds of books on a bookshelf 32 inches long and 10 inches wide. Thirty pounds is the load in service of a medium weight loaded bookshelf being equivalent to 43 pounds of books on a bookshelf 32 inches x 10 inches wide; whereas 60 pounds is probably more typical of the load in service of a very heavily loaded bookshelf, being approximately equivalent to 85 pounds of books on a bookshelf 32 inches x 10 inches wide.

The preceding practical load estimations were based on the fact that the weight of a 1 inch x 10 inch x 10 inch heavy paper bonded book or magazine is approximately 2 to 3 pounds. A 32 inch x 10 inch wide bookshelf should have enough space for 32 heavy books. All the estimated loads

Table 4.--Constant load levels expressed in terms of percentage of stresses at pro-

Table 4.--Constant load levels expressed in terms of percentage of stresses at proportional limit and ultimate strength of the specimens at three different humidities

Specimens	Stress	Constant Load Levels								
		10 pounds			30 pounds			60 pounds		
		30% R.H.	65% R.H.	90% R.H.	30% R.H.	65% R.H.	90% R.H.	30% R.H.	65% R.H.	90% R.H.
3/4 inch particleboard	P.L. (%)	20	20	29	60	60	86	>100	>100	>100
	U.L. (%)	9	8	10	26	23	29	52	46	57
1/36 inch walnut veneered particleboard	P.L. (%)	10	10	10	30	30	30	60	60	60
	U.L. (%)	4	3	4	11	10	12	22	21	23
1/8 inch walnut veneered particleboard	P.L. (%)	4	5	8	12	15	23	24	30	46
	U.L. (%)	2	2	3	6	6	10	12	13	20
3/16 inch walnut veneered particleboard	P.L. (%)	3	5	10	10	15	30	20	30	60
	U.L. (%)	2	2	3	5	6	9	10	12	19
3/4 inch solid walnut	P.L. (%)	3	3	5	10	10	15	20	20	30
	U.L. (%)	2	5	2	5	5	6	10	9	12

P.L.--Proportional Limit U.L.--Ultimate Load R.H.--Relative Humidity

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on a 32 inch x 10 inch bookshelf mentioned above were distributed loads.

Following the completion of 100 minutes creep testing, all specimens were oven dried to determine the exact level of moisture content that had been attained under each of the humidity conditions.

Several specimens were subjected to long term creep test for comparison purposes. The time was prolonged from the designated 100 minutes to a one month period of time.

C. Statistical Design of Experiment

The design of total bending, initial (elastic), creep and irrecoverable deflections of the five kinds of specimens with various shelling ratios was performed with three different practical load levels and relative humidities over a series of short term creep tests.

In Table 5, within each of the relative humidity levels (30 per cent, 65 per cent and 90 per cent), shelling ratio was 0.000, 0.074, 0.333, 0.500, and 1.000 on five randomly allocated sub-plots with two replications. Each sub-plot was divided into three parts, respectively: load level with 10 pounds, 30 pounds and 60 pounds.

Statistically, this particular arrangement is called split-plot design. The source of variation and degree of freedom for data gathered from such a design are listed in Table 6.

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Table 5.--Design of experiment (replication two)

A_1														
B_1			B_2			B_3			B_4			B_5		
C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3

A_2														
B_2			B_1			B_4			B_5			B_3		
C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3

A_3														
B_4			B_1			B_5			B_2			B_3		
C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3

Relative Humidity	Sandwich Structure	(Shelling Ratio)	Constant Load
A_1 = 30%	B_1 = 3/4 inch Pt.Bd.	(0.000)	C_1 = 10 lbs
	B_2 = 1/36 inch W.	(0.074)	
A_2 = 65%	B_3 = 1/8 inch W.	(0.333)	C_2 = 30 lbs
	B_4 = 3/16 inch W.	(0.500)	
A_3 = 90%	B_5 = 3/4 inch W.	(1.000)	C_3 = 60 lbs

The results of the analysis of variance for this particular statistical design should be able to supply us a sufficient amount of information regarding the significance levels of the effects of veneer thickness (shelling

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Table 6.--Analysis of variance

Source of Variation	Degree of Freedom
Relative Humidity (A)	(a-1) = 2
B=AD+D (D=Replication)	(a-1)(d-1)+(d-1) = 3
Shelling Ratio (B)	(b-1) = 4
A X B (Interaction)	(a-1)(b-1) = 8
Load Level (C)	(c-1) = 2
A X C (Interaction)	(a-1)(c-1) = 4
B X C (Interaction)	(b-1)(c-1) = 8
A X B X C (Interaction)	(a-1)(b-1)(c-1) = 16
Error	42
Total	89

ratio), load level and humidity on the creep behaviors of the specimens.

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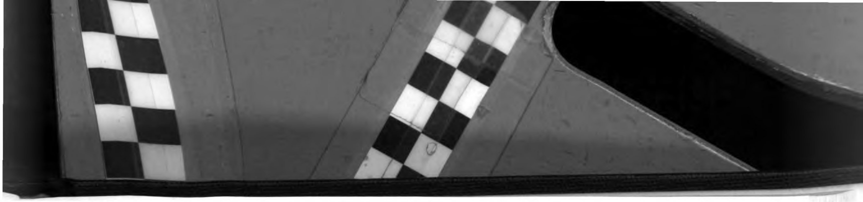
IV. APPROXIMATION OF MAXIMUM CREEP DEFLECTION UNDER SUSTAINED BENDING STRESSES

A. Primary Objective

The maximum bending stresses borne by a veneered particleboard furniture panel such as a book shelf, storage shelf or table top are relatively low in actual service. It is important for us to analyze the resultant condition of the furniture panels, structurally and technically.

First, from the structural point of view, a sustained small bending stress will never cause the panel to fail mechanically. Secondly, an excessive bending deflection which may be associated with the use of particleboard as core material in furniture panels technically does not disturb the service performance. Here, we can conclude that the structural and technical requirements of a veneered particleboard furniture panel are generally small.

However, by looking at the appearance of the furniture panels, excessive deflection or sagging occurring in a good furniture panel is objectionable and undesirable.



This reason has often caused the rejection of particleboard as core material in favor of lumber core board in applications where bending stresses are of long duration.

It is the primary objective of this study to determine the total maximum bending deflection of a veneered particleboard furniture panel under various moisture contents and sustained loading conditions. This particular objective is quite different from those objectives that were previously pursued by other researchers. Their common interests were mainly involved in the study of creep-rupture or time to failure behavior of wood.

B. Definition of Total Maximum Creep Deflection

Under sustained loading, the bending deflection of a particleboard furniture panel consists of two portions, namely short term elastic deflection and long term creep deflection. Long term deflection is due to creep and can not be determined by elastic theory. The creep test results from an experiment of finite duration do not give a true value of maximum creep deflection. It requires an infinite length of time to reach this value. Therefore, it is impossible to determine the true total maximum creep deflection for a furniture panel under sustained practical loading. We will therefore qualify the term of "the total maximum bending or creep deflection" which is used through-o

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out this study as "the estimated total maximum bending or creep deflection."

C. Approximation Techniques

Since it is impossible to determine the true total maximum creep deflection for a furniture panel under sustained practical loading, the only alternative was to develop an approximation technique by which a best estimate of total maximum creep deflection of a veneered particleboard furniture panel under sustained service loading could be provided. This best estimate should be derived from limited results of a short term creep test.

This approximation may be described as follows:

A mathematical form which gave a best fit for short term creep test results as well as long term creep test results was selected from four different mathematical models, namely, semi-log form; power law form; hyperbolic form and polynomial form (9) (Table 7).

After a best fit form had been found, a projection was made by extrapolating the data of the short term creep test. Based on this projection, the time t, at which the rate of creep deflection was considered small enough to be neglected, could be determined. Such rates of creep might be 1/1000 inch per day or per week or 1/10,000 inch per day or per week. The total creep deflection (Y_c) could then be determined for this time t. For practical purposes, Y was

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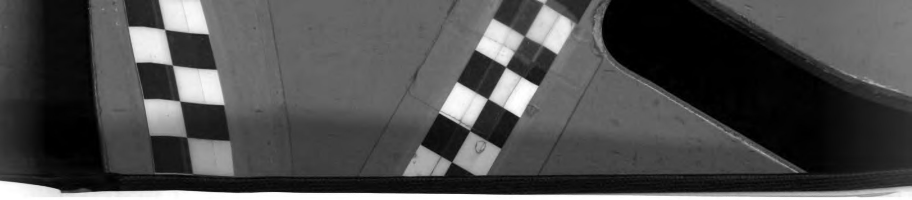
Table 7.--Mathematical models for creep deflection

Models	Formula	t (minutes)
1.	$Y - Y_e = A + B \log (t-1)$	2-100
2. (a)	$Y - Y_e = A(t-1)^{\frac{1}{b}}$	10-100
	or $\log (Y-Y_e) = \log A + \frac{1}{b} \log(t-1)$	
(b)	$Y - Y_e = A(t-1)^{\frac{1}{b}}$	2-10
	or $\log (Y-Y_e) = \log A + \frac{1}{b} \log(t-1)$	
3. (a)	$Y - Y_e = \frac{(t-1)}{A + B(t-1)}$	10-100
(b)	$Y - Y_e = \frac{(t-1)}{A + B(t-1)}$	2-10
4.	$Y - Y_e = A + B(t-1) + C(t-1)^2$	
	$+ \text{-----} J(t-1)^{10}$	2-100

Y = total bending deflection

Y_e = Elastic or Initial Deflection (Deflection at 1 minute)

A,B,b,C,J = constant



assumed to be the best approximation of total maximum bending deflection, such as:

$$Y = Y_e + Y_c \qquad (Y_c = Y_R + Y_{IR})$$

i.e. Y = total maximum bending deflection

Y_e = elastic or initial bending deflection

Y_c = total maximum creep deflection or total plastic deflection

Y_R = recoverable creep deflection

Y_{IR} = irrecoverable creep

A specific computer program was written to make a total bending deflection approximation for every individual specimen of various designs and conditions.

For the purpose of analyzing the reliability of the projection of the creep test results, the results of several long term creep tests were available for comparison.

D. Multivariable Least Square Regression Analysis

A multiple regression analysis was used to develop an expression for total maximum bending deflection $Y(t)$ as functions of panel structures (shelling ratio), load levels, moisture content, and time.

The regression expressions for the total bending deflection $Y(t)$, total creep deflection $Y(t) - Y_e$, and irrecoverable creep deflection (flow) $Y_c(t)-Y_R(t)$ are given:

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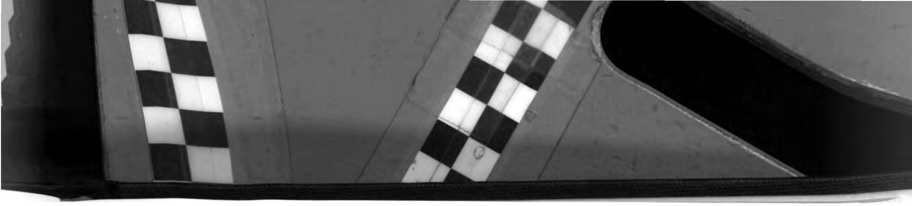


(a) Total bending deflection:

$$Y(t)=f(X_1,X_2,X_3,X_1X_2,X_2X_3,X_1X_3,X_1^2,X_2^2,X_3^2,t)$$

(b) Total creep deflection

$$Y(t)-Y_e=f(X_1,X_2,X_3,X_1X_2,X_2X_3,X_1X_3,X_1^2,X_2^2,X_3^2,t)$$

(c) Irrecoverable creep deflection (flow)

$$Y_c(t)-Y_R(t)=f(X_1,X_2,X_3,X_1X_2,X_2X_3,X_1X_3,X_1^2,X_2^2,X_3^2,t)$$

X_1 = shelling ratio

X_2 = moisture content (per cent)

X_3 = constant load (lbs)

t = time (1) 100 minutes
(2) 1 month
(3) at which the rate of creep is 0.0005 inch per day

$Y(t)$ = total bending deflection

Y_e = elastic or initial deflection

$Y_R(t)$ = recoverable creep deflection

$Y_c(t)$ = total creep deflection

The three expressions (a,b,c) were treated independently by means of back elimination (LSDEL) multiple regression analysis. The terms entered into the expressions were retained if they contributed significantly to the regression and dropped if they did not.

Significance, multiple correlation coefficient and standard error of estimate for the retained terms were examined. Then the estimated deflections could be determined.

V. RESULTS AND DISCUSSION

A. Static Test

1. Test Results

Although static tests were made to determine proper load levels for creep tests, some of the results have general interest, and are therefore reported here in detail.

The results of the static bending tests are shown in Table 8. Each value in the table represents the average of 12 tests. It presents the average value of moisture contents, the standard deviation and the coefficient of variation for the density, modulus of rupture, and the modulus of elasticity for each panel design under three different humidity conditions. The average moisture contents for all specimens were 4.5 per cent, 8.0 per cent and 14.8 per cent, respectively. In general, the coefficient of variations of modulus of rupture were comparatively higher than those of the modulus of elasticity. Density variations were small within each specimen type. Particleboard panels of three thicknesses showed higher density than those of the veneered and 3/4 inch solid walnut panels.

The effect of moisture content on strength of the panels of various design is given in Figure 9. The slope

Table 8.--Static test result (each value is an average for twelve tests)

Specimens	Relative Humidity (%)	Moisture Content (%)	Density (lbs/cu.ft.)			M.O.R. (psi)			M.O.E. (psi)		
			Aver-age	Std. Dev.	C. V.*	Average	Std. Dev.	C. V.*	Average	Std. Dev.	C.V.
3/4 inch solid walnut	30	3.5	35.35	1.69	4.8	15,500	3600	23.2	1,856,000	259,000	14.0
	65	6.5	34.71	0.88	2.5	13,000	3600	27.7	1,851,000	264,000	14.2
	90	15.7	33.92	2.33	6.9	11,700	700	6.0	1,515,000	123,000	8.1
3/16 inch walnut veneered particle-board	30	4.4	41.44	1.46	3.5	14,000	2200	15.7	1,632,000	251,000	15.4
	65	8.0	41.89	1.58	3.9	13,300	2000	15.0	1,587,000	160,000	10.1
	90	14.7	40.30	1.95	4.8	7,600	1200	15.8	1,151,000	180,000	15.6
1/8 inch walnut veneered particle-board	30	4.7	41.91	1.18	2.8	12,200	2800	23.0	1,568,000	156,000	9.9
	65	8.5	42.89	1.99	4.6	11,400	1200	10.5	1,532,000	318,000	20.7
	90	15.0	40.12	1.81	4.5	7,000	700	10.0	1,064,000	195,000	18.3
1/36 inch walnut veneered particle-board	30	4.9	45.08	1.19	2.6	6,000	750	12.5	834,000	131,000	15.7
	65	8.5	44.42	0.95	2.1	5,800	700	12.1	818,000	75,000	9.2
	90	14.2	42.89	1.19	2.9	5,200	300	5.9	607,000	55,000	9.1
3/4 inch particle-board	30	4.7	44.11	1.72	3.9	2,700	400	14.8	471,000	59,000	12.5
	65	8.3	43.90	1.14	2.6	3,000	200	6.7	538,000	53,000	9.9
	90	14.7	42.12	1.61	3.8	2,400	350	14.6	379,000	42,000	11.1

Table 8.--Continued

Specimens	Relative Humidity (%)	Moisture Content (%)	Density (lbs/cu.ft.)			M.O.R. (psi)			M.O.E. (psi)		
			Aver-age	Std. Dev.	C. V.*	Average	Std. Dev.	C. V.*	Average	Std. Dev.	C.V.
1/2 inch particle-board	30	4.3	43.77	1.72	3.9	2,600	250	9.6	512,000	55,000	10.7
	65	8.5	43.40	1.83	4.2	2,700	270	10.0	495,000	41,000	8.3
	90	13.4	41.48	1.66	4.0	2,200	290	13.2	377,000	45,000	11.9
3/8 inch particle-board	30	4.2	46.97	1.69	3.6	3,000	190	6.3	556,000	55,000	9.9
	65	8.2	46.94	1.64	3.5	3,300	260	8.0	555,000	56,000	12.1
	90	13.3	43.69	2.81	6.4	2,400	280	11.7	392,000	50,000	12.9

*C.V. -- Coefficient of variation is equal to the std. dev. expressed as a percentage of the mean.

Figure 9.--The modulus of rupture as function of moisture content

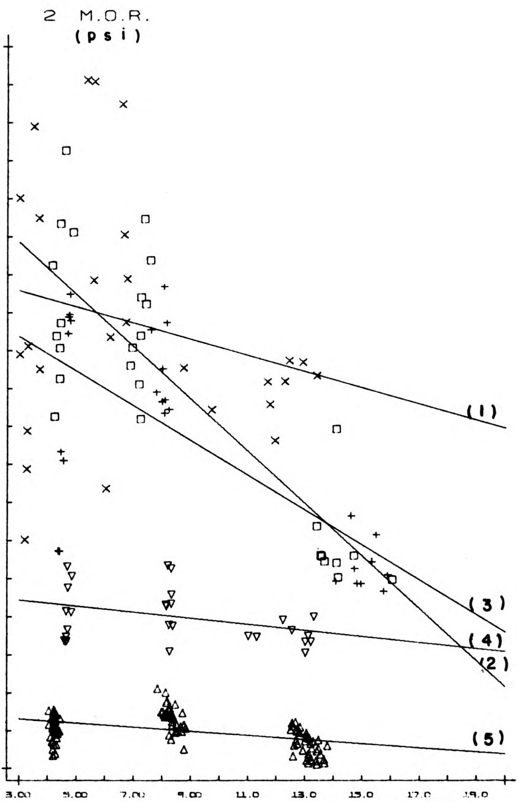
(1) or × : 3/4 inch solid walnut

(2) or □ : 3/16 inch walnut veneered particleboard

(3) or + : 1/8 inch walnut veneered particleboard

(4) or ∇ : 1/36 inch walnut veneered particleboard

(5) or Δ : particleboard



1

SANDWICH PANEL

which represents particleboard shows the combined results of the particleboards at 3/4 inch, 1/2 inch and 3/8 inch thicknesses. Three-fourths inch solid walnut was approximately four times stronger than the particleboard. After the particleboard had been veneered with a 1/36 inch walnut veneer on both faces, the bending strength of the panel was doubled. Within the moisture content range of 3 per cent to 8 per cent, the modulus of rupture was very much the same for a 3/4 inch solid walnut panel and a 3/16 inch walnut wood laminated particleboard panel (at a shelling ratio of 0.500).

Modulus of elasticity results are also given in Table 7 and plotted in Figure 10. Here the effect of moisture content is similar to that of modulus of rupture. The stiffness values continued to increase as the moisture content level was reduced below 13 per cent for all panels with the possible exception of the unveneered particleboard. The veneered panels were affected similarly, losing approximately 15-85 per cent of their strength and 23-47 per cent of their stiffness in going from low moisture content to values approaching 14.8 per cent. This indicates that both solid wood and urea-formaldehyde resin lose strength and stiffness at high humidities. In Figure 10, the slopes representing five different panel design are almost parallel to one another and are in good order for comparison.

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Modulus of elasticity measurements are also given in Table 7 and plotted in Figure 10. Here the effect of mois-ture content is similar to that of modulus of rupture. The stiffness values continued to increase as the moisture con-tent level was reduced below 13 per cent for all panels with the possible exception of the unveneered particle-board. The veneered panels were affected similarly, losing approximately 15-85 per cent of their strength and 22-47 per cent of their stiffness in going from low moisture con-tent to values approaching 14.6 per cent. This indicates that both solid wood and urea-formaldehyde resin lose strength and stiffness at high humidities. In Figure 10, the slopes representing five different panel design are almost parallel to one another and are in good order for comparison.

Figure 10.--The modulus of elasticity as function of moisture content

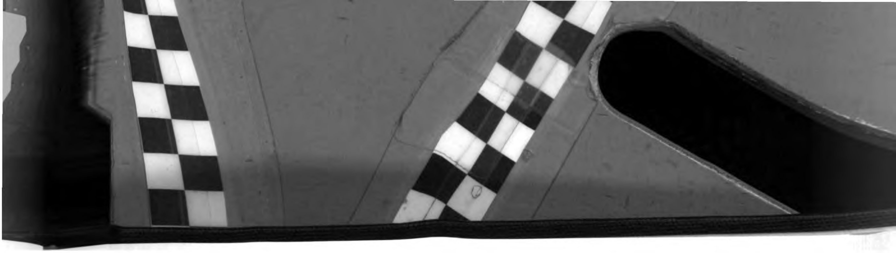
1 or × : 3/4 inch solid walnut

2 or □ : 3/16 inch walnut veneered particleboard

3 or + : 1/8 inch walnut veneered particleboard

4 or ∇ : 1/36 inch walnut veneered particleboard

5 or Δ : particleboard



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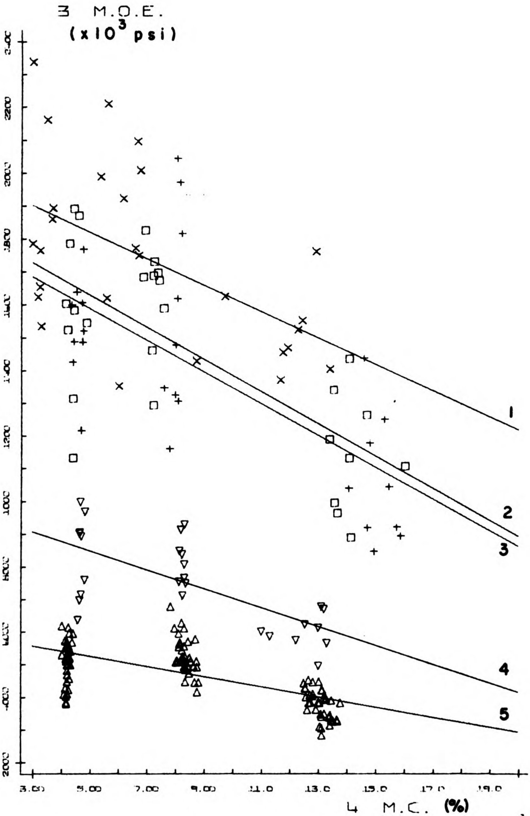

1

SANDWICH PANEL

The regression equations of modulus of elasticity as function of moisture content representing five different specimens designs are listed below:

(a)	3/4 inch solid walnut:	$Y_E = 2026218 - 40179X$
(b)	3/16 inch walnut veneered particleboard:	$Y_E = 18777466 - 48951X$
(c)	1/8 inch walnut veneered particleboard:	$Y_E = 1833523 - 48327X$
(d)	1/36 inch walnut veneered particleboard	$Y_E = 996874 - 28777X$
(e)	3/4 inch particleboard:	$Y_E = 557047 - 11153X$

in which Y_E = modulus of elasticity (psi)

X = moisture content (%)

Similar relationships between modulus of elasticity and moisture content in wood were found by Kollman (16) and others. On parallel to the grain of spruce, in the moisture content range between approximately 8 and 22 per cent the curves may be replaced by straight lines which are extended to the abscissa. The point of intersection will have the absicissa value b. Kollmann suggested a general form as follows:

$$E_2 = E_1 \frac{b-\mu_2}{b-\mu_1} \ (kp/cm^2)$$

in which E_2 = predicted stiffness at moisture content μ_2

The regression equations of modulus of elasticity as function of moisture content concerning five different specimens designs are as follows:

(a) 3/4 inch solid walnut Y_E = [illegible] − 40179X

(b) 3/16 inch walnut veneered particleboard Y_E = [illegible] − 16951X

(c) 1/8 inch walnut veneered [illegible] Y_E = [illegible] − 18321X

(d) 1/36 inch walnut veneered [illegible] [illegible] Y_E = [illegible] − 26777X

(e) 3/4 inch particleboard Y_E = [illegible] − 11153X

in which Y_E = modulus of elasticity (psi)

X = moisture content (%)

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$$E_2 = E_1 \frac{b-u_2}{b-u_1} \ (Kp/cm^2)$$

in which E_2 = predicted stiffness at moisture content u_2

E_1 = determined stiffness at moisture content μ_1

b = absicissa value

The static test experimentally confirmed that the face wood material with relative high strength and stiffness properties greatly increased the bending strength and stiffness of the particleboard core panel, Even in the form of very thin veneer facing, this material still contributed substantially to the strength and stiffness of the resulting composite. Stress distributions in wood and in composite panels at time of maximum bending moment are shown in Figures 11a and 11b (5). They illustrate the contribution of face veneer to the over-all strength of the composite, increasing value for composite bending stresses, corresponding to an additional layer of the face wood veneer.

2. Prediction of Stiffness Property in Veneered Particleboard Composite Beams (at proportional limit)

Three methods of analysis were used in comparing actual test stiffness values with predicted stiffness values based on mechanical theory. The first and second of these neglected shear deflection in the core particleboard or assumed that the core particleboard behaved in the composite beam exactly as it behaved when loaded by itself as a simple beam. Modulus of elasticity values computed for each composite beam center loaded at a thickness-span ratio of

E_1 = determined stiffness at moisture content [illegible]

k = abscissa value

The static test experimentally confirmed that the face wood material with [illegible] strength and stiffness properties [illegible] the bending strength and stiffness of the particleboard [illegible] panel. Even in the form of very thin veneer, the [illegible] material still contributed substantially [illegible] strength and stiffness of the resulting composites. [illegible] in wood and in composite panels at time of [illegible] bending moment are shown in Figures [illegible] They illustrate the contribution of face [illegible] strength of the composite, increasing [illegible] composite bending stresses, corresponding to an [illegible] layer of the face wood veneer.

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Figure 11(a).--Stress distribution in wood at time of maximum bending moment

S_c = ultimate compressive strength

S_t = ultimate tensile strength

y = distance to neutral axis

(b).--Stress distribution in balanced sandwich panel at time of maximum bending moment

S_{co} = ultimate compressive strength of veneer layer

S_{ci} = ultimate compressive strength of core

S_{to} = ultimate tensile strength of veneer layer

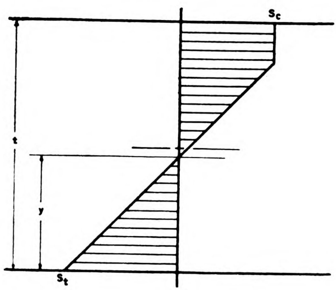
S_{ti} = ultimate tensile strength of core

t_c = surface veneer thickness on compression side

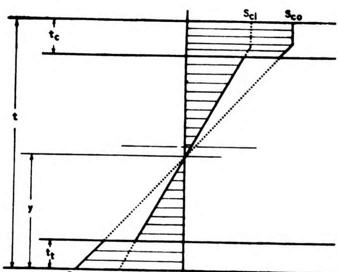
t_t = surface veneer thickness on tension side

y = distance to neutral axis

(See Reference 32)



(a)



(b)

1:24, as well as values for composite beams of each core particleboard are shown in Table 8.

In the analysis of method 1

$$\hat{E} = \frac{E_f I_f + E_c I_c}{I} \qquad \text{(see reference 9)}$$

in which $\hat{E}$ and I are predicted modulus of elasticity and moment of inertia of the composite, respectively. E_f and I_f are the corresponding values for the facing and E_c and I_c are corresponding values for the core.

By the second method of analysis, for a sandwich beam of symmetrical cross section and identical face material on both sides:

$$E = E_f - (1-\lambda)^3 (E_f - E_c) \qquad \text{(see references 15 and 32)}$$

where E_f = modulus of elasticity of faces

E_c = modulus of elasticity of core

λ = shelling ratio

Predicted values which were obtained from method one and method two for actual E, are shown in Table 9. To facilitate examination of the data, the ratio of calculated to actual moduli was plotted against the shelling ratios and moisture content conditions for all composite beams (Figure 12).

The predicted values of methods 1 and 2 were almost identical in all humidities. Their values were high,

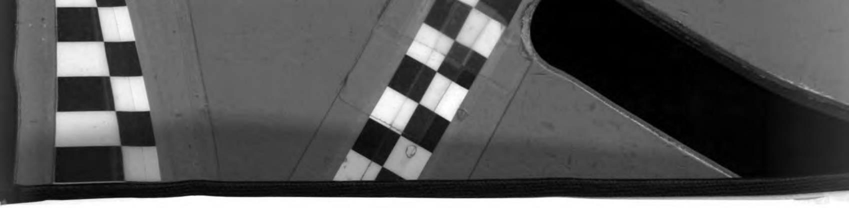


Table 9.--Predictions of M.O.E. for walnut veneered sandwich beams

	Relative Humidity (%)	Particleboard Core					Sandwich Beams (Method 1)			Sandwich Beams (Method 2)		
		M.C. (%)	Density (lbs/cu.ft.)	Tested MOE (100 psi)	Pure MOE (100 psi)	M.O.R. (G_{LT}) (100 psi)	Actual MOE (100 psi)	Predicted MOE (100 psi)	Difference (%)	Actual MOE (100 psi)	Predicted MOE (100 psi)	Difference (%)
1/36 inch walnut + 3/4 inch particleboard + 1/36 inch walnut	30	4.7	44.11	4707	5780	66	8337	9166	+ 9.9	8337	8972	+ 7.6
	65	8.3	43.90	5383	6536	79	8182	9706	+18.6	8182	9667	+18.1
	90	14.7	42.12	3789	4951	52	6068	7830	+29.0	6068	8050	+32.7
1/8 inch walnut + 1/2 inch particleboard + 1/8 inch walnut	30	4.3	43.77	5116	6849	59	15683	16957	+10.7	15683	16995	+11.0
	65	8.5	43.40	4952	6667	59	15316	17179	+ 9.5	15316	17267	+10.0
	90	13.4	41.48	3772	5937	25	10643	16388	+54.0	10643	16419	+54.2
3/16 inch walnut + 3/8 inch particleboard + 3/16 inch walnut	30	4.2	46.97	5560	7407	44	16322	19534	+23.1	16322	19542	+23.1
	65	8.2	46.94	5548	7299	47	15869	19792	+21.2	15869	19811	+21.4
	90	13.3	43.69	3920	6636	24	11509	18408	+59.9	11509	18454	+60.3

Table 9.--Continued

	Sandwich Beams (Method 3)		
	Actual MOE (100 psi)	Predicted MOE (100 psi)	Difference (%)
1/36 inch walnut + 3/4 inch particleboard + 1/36 inch walnut	8337	7720	- 7.9
	8182	7692	- 6.0
	6068	5870	- 3.3
1/8 inch walnut + 1/2 inch particleboard + 1/8 inch walnut	15683	11821	-24.6
	15316	11172	-27.1
	10643	9597	- 9.8
3/16 inch walnut + 3/8 inch particleboard + 3/16 inch walnut	16322	12289	-24.7
	15869	11634	-26.7
	11509	9807	-16.6

Table 8.--[illegible]

	Rela-tion	M.C. (%)	Density (lbs./cu.ft.)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Difference (%)	[illegible]	[illegible]	Difference (%)
1/36 inch walnut + [illegible]	30	4.7	44.1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	43.90	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1/36 inch walnut	90	14.7	42.12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1/8 inch walnut + [illegible]	30	4.3	43.77	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] board +	[illegible]	[illegible]	[illegible]	4952	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1/8 inch walnut	90	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3/16 inch walnut +	30	4.2	46.97	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3/8 inch particle-board +	65	8.2	46.94	[illegible]	[illegible]	47	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3/16 inch walnut	90	13.3	43.69	3920	6636	24	11509	18408	+59.9	11509	18454	+60.1

Figure 12.--The ratio of predicted M.O.E. to actual tested M.O.E. as function of shelling ratio

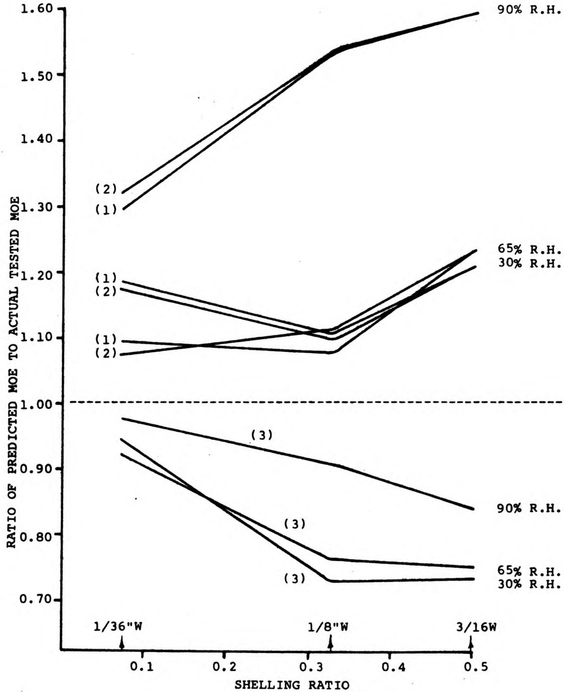
(1) $$\hat{E} = \frac{E_c I_c + E_f I_f}{I}$$

(2) $$\hat{E} = E_f - (1-\lambda)^3 (E_f - E_c)$$

(3) $$y = \frac{Pl^3}{48(E_c I_c + E_f I_f)} + \frac{Pl}{2(d+c)bG}$$

$$\hat{E} = \frac{Pl^3}{4bd^3 y}$$

R.H.--Relative humidity (per cent)



RATIO OF PREDICTED MOE TO ACTUAL TESTED MOE
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
90% R.H.
(2)
(1)
65% R.H.
30% R.H.
(1)
(2)
(1)
(2)
(3)
90% R.H.
(3)
65% R.H.
(3)
30% R.H.
1/36"W
1/8"W
3/16W
0.1
0.2
0.3
0.4
0.5
SHELLING RATIO

showing deviations ranging from 7.6 per cent to 60.3 per cent.

The greater discrepancy occurred in the composite beam with high moisture content. The overall high percentage of predicted results could be due to a lack of consideration of shear effect.

The third method of analysis used in this study involved separation of the individual contributions to deflection of the composite beam resulting from (1) deflection as a result of the pure bending and (2) deflection of the core particleboard in shear.

The basic equation used in this calculation was recommended by Kuenzi (17) for computing the deflection of a structural sandwich beam:

$$\hat{y} = \frac{Pl^3}{48(\hat{E}_f I_f + \hat{E}_c I_c)} + \frac{Pl}{2(d+c)bG_t}$$

in which $\hat{y}$ = total deflection (inches)

d = total thickness of beam (inches)

b = width of beam (inches)

G_t = modulus of rigidity of the core particleboard (psi)

$\hat{E}_f, \hat{E}_c$ = pure modulus of elasticity of face and core (psi) (infinite ratio between thickness and span)

I_f, I_c = moment of inertia of face and core (inches)

l = span length (inches)

c = core thickness (inches)

P = load at proportional limit (pounds)

In order to obtain G_t, $\hat{E}_f$ and $\hat{E}_c$, the technique developed by Timoshenko (36) and Preston (27) was adapted in this study.

In Table 9 and Figure 12, all predicted values for actual E, based on the third method of analysis, were lower than those actually developed. The predicted values were low, showing deviations ranging from 3.3 per cent to 27.1 per cent for all humidities and composite structures. However, in predicting the stiffnesses of a 1/36 inch veneered particleboard sandwich beam at all humidity conditions and 1/8 inch and 3/16 inch veneered particleboard sandwich beams at high humidity, the values obtained by method 3 were relatively more accurate than those developed by method 1 and 2.

In view of all predicted values for actual E, particularly in the extreme humidity condition of 90 per cent the major defect is apparent in the first and second methods of predicting modulus of elasticity for composite beams, which neglected shear deflection. On the theoretical and experimental basis, the third method of analysis, which takes into account shear contribution to deflection, should be applicable over a wide range of moisture content conditions and is recommended for predicting the modulus of elasticity of veneered particleboard furniture panels.

3. Shear Deflection

In computing deflection of wood beams in static bending with central loading, usually only the deflection due to pure bending is considered. The deflection due to shear is assumed to be negligible and is not considered in computing the total deflection of a beam. In the case of a composite beam, due to the development of greater shear stresses, shear deflection should be considered. It is important to know the relative contribution of shear deflection to the total deflection of the veneered particleboard composite beams in static bending.

By using the techniques developed by Timoshenko (36) and Preston (27), the results of total bending deflection due to pure bending and shear were obtained and listed in Table 10. From Figure 13 it can be seen that the deflection due to shear can become considerable, reaching 20, 35 and 46 per cent of the total deflection at shelling ratios of 0.074, 0.333 and 0.500, respectively, for the composite beams. It is shown here that the percentage of shear deflection can be considerable, approaching the amount due to pure bending. Furthermore, it is shown that the magnitude of the shear deflection depends on both the shelling ratios of the composite beam and the relative humidity conditions of the environment. The shear deflection increases with increasing shelling ratios of the veneered particleboards

Table 10.--Pure bending deflection and shear deflections of composite beams

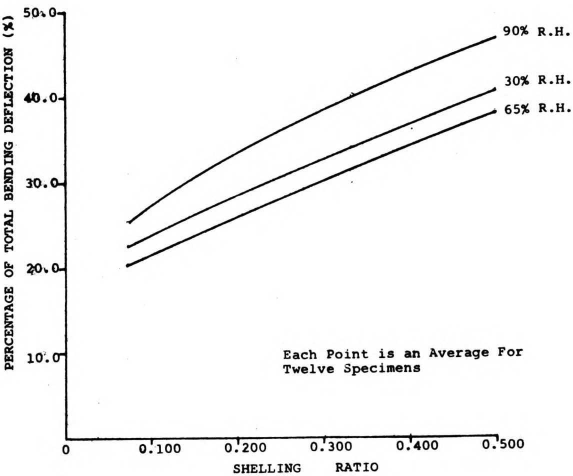
	Relative Humidity	Pure Bending Deflection (inches)	Percentage of Pure Bending Deflection (%)	Shear Deflection (inches)	Percentage of Shear Deflection (%)	Total Deflection
1/36 inch w	30	0.1843	77.68	0.0530	22.32	0.2373
	65	0.1629	79.25	0.0427	20.75	0.2056
	90	0.1653	74.98	0.0551	25.02	0.2204
1/8 inch w	30	0.2787	65.89	0.1442	34.11	0.4229
	65	0.2017	68.81	0.0914	31.19	0.2931
	90	0.1156	58.56	0.0819	41.44	0.1976
3/16 inch w	30	0.2631	59.56	0.1786	40.44	0.4417
	65	0.1814	62.04	0.1114	37.96	0.2928
	90	0.1065	53.28	0.0932	46.72	0.1997

$$y = \frac{Pl^3}{48(E_cI_c + E_fI_f)} + \frac{Pl}{2(c+d)bxG_T}$$ P=load at proportional limit

under all humidities. Highest shear deflection values are obtained at 90 % humidity.

Figure 13.--The percentage of total bending deflection due to shear as function of shelling ratio

R.H. -- Relative humidity (per cent)



PERCENTAGE OF TOTAL BENDING DEFLECTION (%)
50.0
40.0
30.0
20.0
10.0
0
0.100
0.200
0.300
0.400
0.500
SHELLING RATIO
90% R.H.
30% R.H.
65% R.H.
Each Point is an Average For
Twelve Specimens

B. Creep Test

1. Creep Limit

The creep limit is defined as "the maximum value of stress or load which will produce a rate of creep which approaches zero as time increases" (35). It can also be defined as "the maximum value of sustained stress withstood by a specimen without causing failure." It is difficult to evaluate the creep limit by the application of the latter definition, because of the amount of time required to gather meaningful data. An effective method which in general can determine the creep limit within a limited period of time can be obtained by using the former definition.

If a constant load or stress which is applied to a specimen is above the creep limit, the creep progresses freely without any restraint until the specimen fails. On the other hand, if a constant load or stress which is applied to a specimen is below the creep limit, this constant load can be considered as a safe load for this specimen. In order to be assured that the specimens eventually will never fail under the certain applied constant load levels, it is important to determine the creep limits for the furniture panels of various designs so that a safe constant load for individual specimens used in this experiment may be estimated.

By introducing the Sugiyama technique (35), which is adopted to determine the creep limit in "Test Method of

Wood" in Japanese Industrial Standards, the estimated creep limit was determined and is shown for individual specimens in Table 11. It is good to know the safe load regions for the specimens of particular dimension and composite designs in the experiments. Table 11 indicates that 10 pounds, 20 pounds and 30 pounds constant loads may be considered safe loads for all specimens and humidity conditions, except the 3/4 inch particleboard at high humidity conditions. In the case of 60 pounds constant load, it was termed unsafe to be used on 3/4 inch particleboard of all three humidity conditions.

The result shows that the influence of moisture content on the creep limit in bending is not negligible and that the creep limit in bending should be considerably reduced for materials with a high moisture content.

It can be concluded from the results of this test that the load at the creep limit in bending corresponds to approximately 60 per cent of the load at the proportional limit in the static bending test for all specimens of various designs (Table 4).

2. Short Term Creep Test

Results

The results of analysis of variance for this specially designed split-plot experiment are shown in Table 12. The significance levels of all factors and interactions were less than 0.9 per cent. Most of the significance

Table 11.--Result of creep limit test

	10 lbs			20 lbs			30 lbs			60 lbs			120 lbs			200 lbs		
	30 %	65 %	90 %	30 %	65 %	90 %	30 %	65 %	90 %	30 %	65 %	90 %	30 %	65 %	90 %	30 %	65 %	90 %
3/4 inch Pt. Bd.	S	S	S	S	S	S	S	S	F	F	F	F	F	F	F	F	F	F
1/36 inch W	S	S	S	S	S	S	S	S	S	S	S	S	F	F	F	F	F	F
1/8 inch W	S	S	S	S	S	S	S	S	S	S	S	S	S	S	F	F	F	F
3/16 inch W	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	F	F	F
3/4 inch W	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	F

S -- Safe load (within creep limit)
F -- Failure (beyond creep limit)

Creep limit is the highest load whose sustained application can be indefinitely endured without failure.

Table 12.--Result of analysis of variance (split-plot design)

Source of Variation	Degree of Freedom	Approx. Significance Probability of F Statistics			
		$Y-Y_1$	Y	Y_1	$Y-Y_R$
Relative Humidity (A)	2	0.009	0.0040	0.003	<0.0005
Z = AD+D (D = Replication)	3				
Shelling Ratio (B)	4	<0.0005	<0.0005	<0.0005	<0.0005
A x B (Interaction)	8	<0.0005	<0.0005	<0.0005	<0.0005
Load Level (C)	2	<0.0005	<0.0005	<0.0005	<0.0005
A x C (Interaction)	8	<0.0005	<0.0005	<0.0005	<0.0005
B x C (Interaction)	4	<0.0005	<0.0005	0.001	<0.0005
A x B x C (Interaction)	16	<0.0005	<0.0005	0.002	<0.0005
Remaining Error	42				
Total	89				

Y = total bending deflection

Y_1 = initial (elastic) deflection

Y_R = recoverable deflection

$Y-Y_1$ = creep deflection

$Y-Y_R$ = irrecoverable deflection (flow)

levels were below 0.05 per cent. This indicates that all the dependent variables of total bending, initial, creep and irrecoverable deflections were significantly affected by the independent variables of humidities, shelling ratio of the veneered particleboard, constant load levels and their interactions in this experiment.

A typical representative creep or recovery-time relationship is shown in Figure 14. Total bending, creep and irrecoverable deflections as functions of shelling ratio, load levels and relative humidities at 100 minutes are shown in Figures 15, 16 and 17. Figure 18 shows the total and initial bending deflection as functions of shelling ratio and humidities with a constant load of 30 pounds at 100 minutes testing period.

The results emphasize that moisture content in particleboard, veneered particleboard and solid walnut wood plays an important role in the viscoelastic behavior exhibited by these materials.

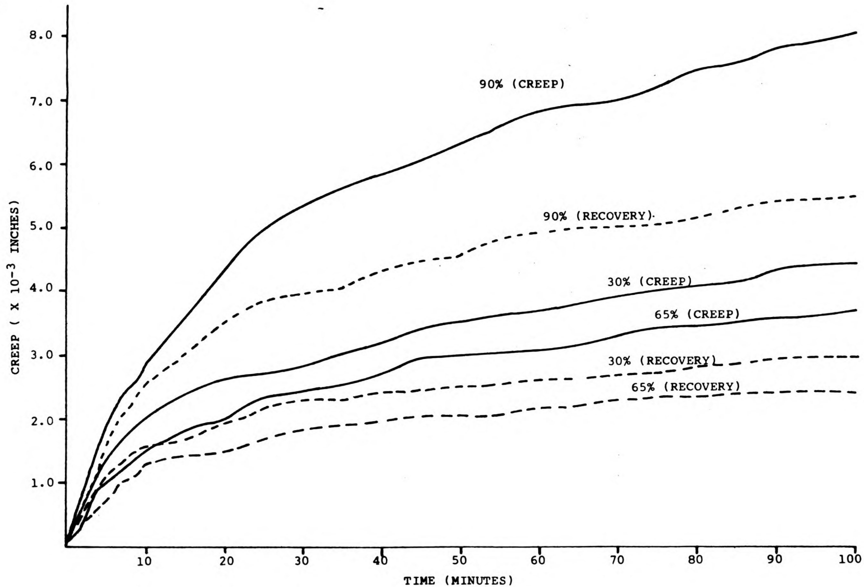
Maximum bending, creep and irrecoverable deflection values were obtained at 90 per cent humidity for all specimens. The creep values of the 3/4 inch particleboard with a shelling ratio of zero were at a minimum at 65 per cent humidity, but that at lower or higher humidities the creep values were greater. However, the higher creep deflection in the particleboard at low humidity is a phenomenon levels were below 0.05 per cent. This indicates that all the dependent variables of total bending, initial, creep and irrecoverable deflections were significantly affected by the independent variables of humidities, shelling ratios of the veneered particleboard, constant load levels and their interactions [illegible] per cent).

A typical [illegible] recovery-time relationship is shown in [illegible] total bending, creep and irrecoverable [illegible] of shelling ratio, load levels and [illegible] at 100 minutes are shown in Figures 16, [illegible] Figure 18 shows the total and initial bending [illegible] functions of shelling ratio and humidity [illegible] constant load of 30 pounds at 100 minutes testing period.

The results emphasize that moisture content in particleboard, veneered particleboard and solid walnut wood plays an important role in the viscoelastic behavior exhibited by these materials.

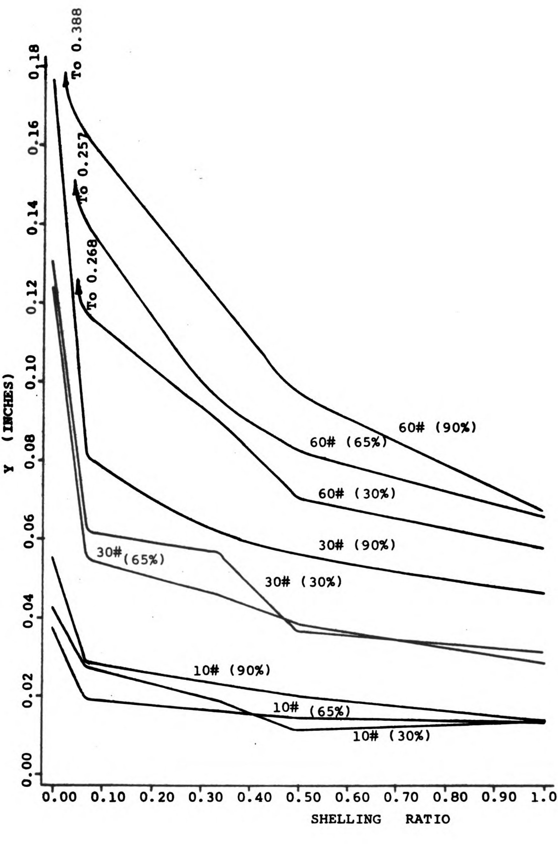
Maximum bending, creep and irrecoverable deflection values were obtained at 90 per cent humidity for all specimens. The creep values of the 3/4 inch particleboard with a shelling ratio of zero were at a minimum at 65 per cent humidity, but that at lower or higher humidities the creep values were greater. However, the higher creep deflection in the particleboard at low humidity is a phenomenon

Figure 14.--The relationship between creep or recovery and time as the 1/36 inch walnut veneered particleboard containing high (90 per cent), medium (65 per cent), and low (30 per cent) relative humidities (constant load level -- 30 pounds).



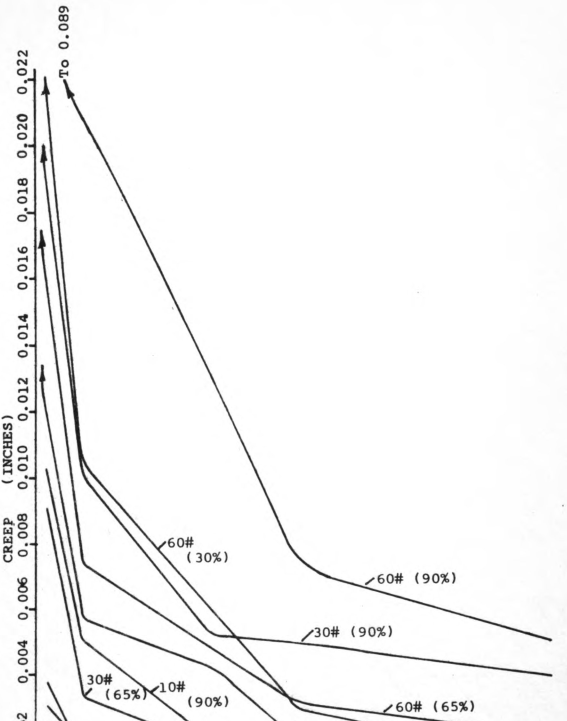
90% (CREEP)
90% (RECOVERY)
30% (CREEP)
65% (CREEP)
30% (RECOVERY)
65% (RECOVERY)
CREEP (X 10-3 INCHES)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
10
20
30
40
50
60
70
80
90
100
TIME (MINUTES)

Figure 15.--Total bending deflection (Y) as function of shelling ratio, load level, and relative humidity (at 100 minutes)



Y (INCHES)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
To 0.388
To 0.257
To 0.268
60# (90%)
60# (65%)
60# (30%)
30# (90%)
30# (65%)
30# (30%)
10# (90%)
10# (65%)
10# (30%)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
SHELLING RATIO

Figure 16.--Total creep deflection as function of shelling ratio, load level, and relative humidity (at 100 minutes)



CREEP (INCHES)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
0.020
0.022
To 0.089
60# (30%)
60# (90%)
30# (90%)
30# (65%)
10# (90%)
60# (65%)
30# (30%)
10# (65%)
10# (30%)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
SHELLING RATIO

Figure 17.--Flow (Y_C-Y_R) as function of shelling ratio, load level, and relative humidity (at 100 minutes)

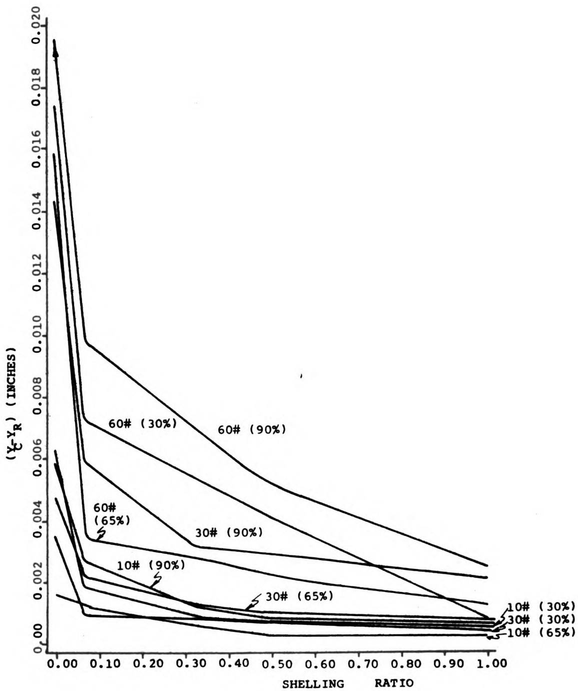
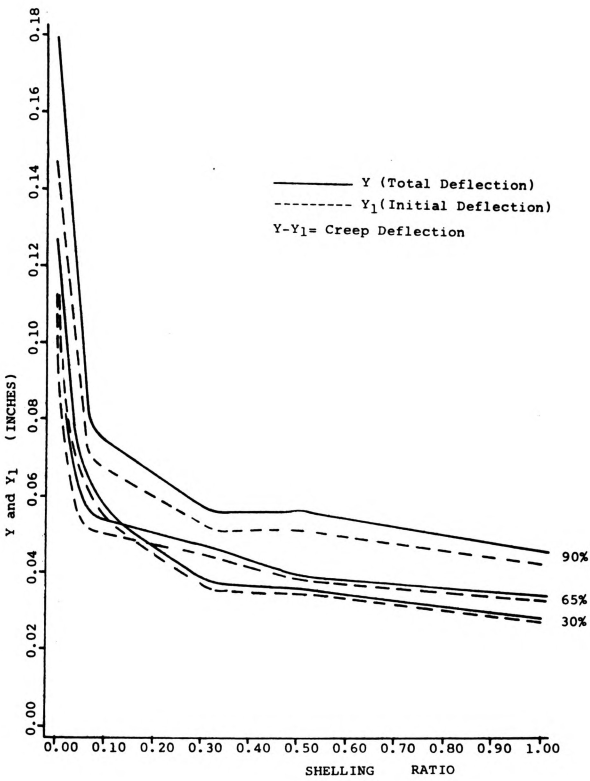

0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.00
(Y_C-Y_R) (INCHES)
60# (30%)
60# (90%)
60#
(65%)
30# (90%)
10# (90%)
30# (65%)
10# (30%)
30# (30%)
10# (65%)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
SHELLING RATIO

Figure 18.--Total deflection and initial (elastic) deflection as function of shelling ratio and relative humidity at a constant load of 30 pounds (at 100 minutes)



Y (Total Deflection)
Y1(Initial Deflection)
Y-Y1= Creep Deflection
Y and Y1 (INCHES)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
SHELLING RATIO
90%
65%
30%

of which one reasonable explanation appears to be as follows:

At intermediate moisture contents, residual stresses are released (18); thus the over-all load capacity of particleboard is increased. On the other hand, the glue bonds among wood particles of particleboard are believed to be highly bonded at the 65 per cent humidity condition.

In all cases, creep deflections were increased as the time and load were increased.

It may be noted that the initial and creep deflections under a given bending load were reduced by more than half under all humidity conditions by the application of a very thin 1/36 inch walnut veneer on both sides of the particleboard. By gradually increasing the veneer thickness or shelling ratio of the composite, creep deflections were further reduced but at a slower rate up to the veneer thickness of 3/16 inch or with a shelling ratio of 0.500. It can be described in such a way that a very similar performance of creep deflection as solid wood can be achieved by using the veneered particleboard composite with a shelling ratio of 0.500.

Irrecoverable creep or permanent set increased with decreasing shelling ratio and increasing constant loads. Recoverable and irrecoverable creeps are the results of the molecular processes (28). Irrecoverable creep is the result of failure to restore forces that were temporarily locked into the structure because the molecules cannot be restored to their original position in the board structure at high humidity condition (11).

3. Results of Approximation Techniques and Best Approximation of Total Maximum Bending and Creep Deflections

The creep-time relationship was found to be satisfactorily fitted by a power law equation of the general type:

$$Y-Y_e = A(t-1)^{\frac{1}{b}} \quad \text{- - - - - - - - - -} \quad (1)$$

where Y = total bending deflection

Y_e = initial deflection at 1 minute

t = time in minutes

A, b = constant Let $\frac{1}{b} = B$

It was discovered that the results yielded a straight line when the logarithm of creep deflection was plotted against that of time. The plot led to an equation:

$$\log (Y-Y_e) = \log A + \frac{1}{b} \log (t-1) \quad \text{- - - - - -} \quad (2)$$

into the structure because the [illegible] cannot be restored to their original position in the [illegible] structure at high humidity condition (11).

3. <u>Results of Approxim[illegible] Techniques and Best Appro[illegible] mation of Total Maxim[illegible] ing and Creep Deflec[illegible]</u>

The creep-[illegible] found to be satis-factorily fitted [illegible] of the general type:

[illegible] - - - - - - - (1)

where Y = total bending deflec[illegible]

Y_e = initial deflec[illegible] at 1 minute

t = time in minutes

A, b = constant[illegible] let $\frac{1}{b} = B$

It was discovered that the results yielded a straight line when the logarithm of creep deflection was plotted against that of time. The plot led to an equation:

$$\log (Y-Y_e) = \log A + \frac{1}{b} \log (t+1) \quad - - - - - - - (2)$$

This form is a straight line in the dependent variables $\log (Y-Y_e)$ with slope $\frac{1}{b}$ and x intercept log A. These slope and intercept constants can be solved by least square method.

The relation between total bending deflection and time was most accurately described by a three-stage relationship consisting of an initial (elastic) deflection at one minute plus a power law linear regression of 2-10 minutes and a major power law linear regression of 10 minutes and up thereafter. The total bending deflection under sustained loading can be divided into three portions:

$$Y = Y_e + Y_1 + Y_2 \quad \text{- - - - - - - - - - - - - - -} \quad (3)$$

in which Y_e = elastic or initial deflection at one minute

$Y_1 = A(t-1)^B \qquad 1<t\leq 10$ (minutes)

$Y_2 = A(t-1)^B \qquad 10\leq t\leq \infty$ (minutes)

Yc = total creep deflection

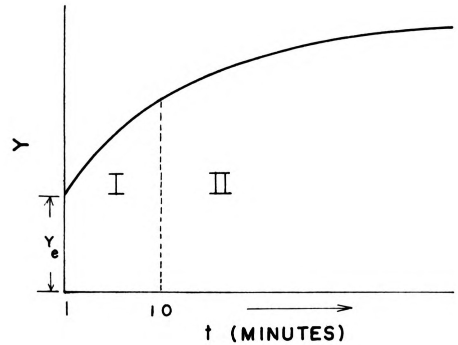
$Yc = Y_1 + Y_2$

Figures 19(a) and 19(b) describe three stages of relationship between total bending deflections under sustained loading conditions and time in this experiment.

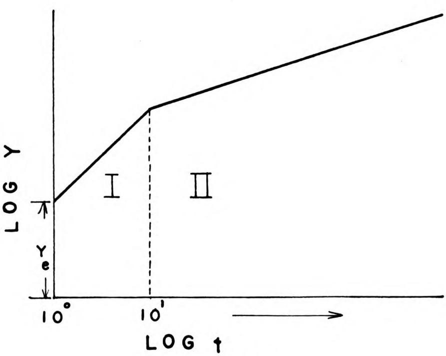
Figure 19(a).--The relationship between total bending deflection (Y) and time

Ye = initial deflection at one minute

(b).--The relationship between total bending deflection and time (Log-Log scale)



(a)



(b)

In Figure 20, the time of three short term creep tests was extended to a period of 30 days. In speaking of the conditions of these specimens, a 10 pound constant load was applied on a 3/4 inch solid walnut specimen under a relative humidity condition of 65 per cent and two 1/36 inch walnut veneered particleboard composite specimens were constantly loaded with a 30 pound weight at the humidity conditions of 65 per cent and 90 per cent, respectively. It appeared that the projections which were made by extrapolating the creep data of short term creep test between 10-100 minutes were found to be satisfactory to predict the long term creep results. Based on the projections, the time "t" for various rates of creep such as 0.0001 inch; 0.0005 inch; 0.001 inch; 0.005 inch; 0.01 inch per day, per week, and per month were determined by taking the slope of equation (1) as follows:

$$\frac{dY}{dt} = \frac{A}{b}(t-1)^{\frac{1}{b}-1} \quad \text{- - - - - - - - - - - - - - - - - -} \quad (4)$$

$$\log \left(\frac{dY}{dt}\right) = \log A - \log b + \left(\frac{1}{b}-1\right) \log (t-1)$$

$$\left(\text{Let } \log b = -\log B \qquad \frac{1}{b} = B,\ b = \frac{1}{B}\right)$$

$$\therefore \log (t-1) = \frac{\log \frac{dY}{dt} - \log A + \log B}{B - 1} \quad \text{- - - -} \quad (5)$$

In Figure 20, the time of three short term creep tests was extended to a period of [illegible] days. In speaking of the conditions of these specimens, a 10 pound constant load was applied on a 3/4 inch solid walnut specimen under a relative humidity condition of [illegible] percent and two 1/36 inch walnut veneered particleboard [illegible] the specimens were constantly loaded with [illegible] pound weight at the humidity conditions of 65 per cent and [illegible] respectively. It appeared that the computations which were made by extrapolating the creep data of short term creep test between 10-100 minutes were found to be satisfactory to predict the long term creep results. Based on the predictions, the time "t" for various rates of creep such as 0.0001 inch; 0.0005 inch; 0.001 inch; 0.005 inch; 0.01 inch per day, per week, and per month were determined by taking the slope of equation (1) as follows:

$$\frac{dY}{dt} = \frac{A}{b}(t-1)^{\frac{1}{b}-1} \quad \text{-------------------} \quad (4)$$

$$\log \left(\frac{dY}{dt}\right) = \log A - \log b + \left(\frac{1}{b}-1\right) \log (t-1)$$

$$\left(\text{Let } \log b = -\log B \qquad \frac{1}{b} = B, \; b = \frac{1}{B}\right)$$

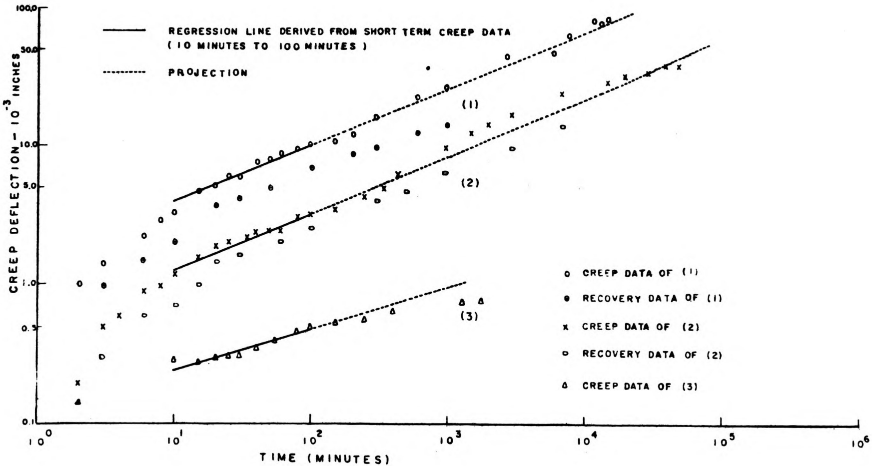
$$\therefore \log (t-1) = \frac{\log \frac{dY}{dt} - \log A + \log B}{B - 1} \quad \text{-----} \quad (5)$$

Figure 20.--The comparison between short term and long term creep tests (Log-Log scale)

(1) 1/36 inch walnut veneered particleboard under 30 pounds sustained loading (90 per cent relative humidity condition)

(2) 1/36 inch walnut veneered particleboard under 30 pounds sustained loading (65 per cent relative humidity condition)

(3) 3/4 inch solid walnut under 10 pounds sustained loading (65 per cent relative humidity condition)



REGRESSION LINE DERIVED FROM SHORT TERM CREEP DATA
(10 MINUTES TO 100 MINUTES)
PROJECTION
(1)
(2)
(3)
CREEP DATA OF (1)
RECOVERY DATA OF (1)
CREEP DATA OF (2)
RECOVERY DATA OF (2)
CREEP DATA OF (3)
100.0
30.0
10.0
5.0
1.0
0.5
0.1
CREEP DEFLECTION - 10^{-3} INCHES
10^0
10^1
10^2
10^3
10^4
10^5
10^6
TIME (MINUTES)

Then the total deflections at various rates of creep were obtained from equation (1).

In relating the predicted results at various rates of creep to the actual tested results of long term creep tests, it was decided to consider a creep rate of 0.0005 inch per day, small enough to be disregarded. The total deflections at this particular rate of creep were assumed to be the best approximation of total maximum bending deflection throughout this study.

CDC 3600 computer was programmed to solve:

(1) Constants A and b in equation (1) for specimens of various design and loading conditions.

(2) Corresponding t at a creep rate of 0.0005 inch per day from equation (5).

(3) Best approximation of total maximum bending deflections and total creep deflections for furniture panels of various designs and conditions.

In view of the behavior of the creep recovery test in Figure 20, the results were also fitted well by equation (1). The best approximations of total deflection recovery were made in the same manner as the total creep deflection.

An expression for total maximum bending, creep and irrecoverable (flow) deflections as functions of composite structures (shelling ratios), load levels, moisture contents and time was developed. The results of LSDEL backward elimination multiple regression analysis are shown in Table 13. The listed items include variables considered, multiple correlation coefficient, standard error of estimate,

Table 13.--The backward elimination (LSDEL) multivariable regression analysis

Dependent Variable	Variables Considered	R^2	Standard Error of Estimate	Variables Deleted	Overall F Significance Level
(1) Y	$X_4, X_5, X_6, X_4X_5, X_4X_6$ X_4^2, X_5^2, X_6^2, t	0.9920	0.0593	$X_5X_6, X_4X_5X_6$	<0.0005
Y-Ye	$X_4, X_5, X_6, X_5X_6, X_4X_6$ X_5^2, X_6^2, t	0.9924	0.0528	$X_4X_5, X_4X_5X_6, X_4^2$	<0.0005
Y_c-Y_R	$X_4, X_5, X_6, X_4^2, X_6^2, t$	0.9231	0.0387	$X_4X_5, X_5X_6, X_4X_6,$ $X_5^2, X_4X_5X_6$	<0.0005
(2) Y	$X_4, X_5, X_6, X_4^2, X_6^2, t$ $X_4\ X_6$	0.9623	0.01587	X_4X_5, X_5X_6, X_5^2 $X_4X_5X_6$	<0.0005
Y-Ye	$X_4, X_5, X_6, X_5^2, X_6^2, t$	0.9940	0.00118	X_4X_5, X_4X_6, X_5X_6 $X_4^2, X_4X_5X_6$	<0.0005
Y_c-Y_R	X_4, X_5, X_6, X_4^2, t	0.9646	0.00133	X_4X_5, X_5X_6, X_4X_6 $X_5^2, X_6^2, X_4X_5X_6$	<0.0005

Table 13.--Continued

Dependent Variable	Variables Considered	R^2	Standard Error of Estimate	Variables Deleted	Overall F Significance Level
(3) Y	$X_4, X_5, X_6, X_4X_6, X_5^2, X_6^2, t$	0.9264	0.07610	$X_4X_5, X_5X_6, X_4^2,$ $X_4X_5X_6$	<0.0005
Y-Ye	X_4, X_5, X_6, X_5^2, t	0.9549	0.0276	X_4X_5, X_5X_6, X_4X_6 $X_4^2, X_6^2, X_4X_5X_6$	<0.0005
$Y_c - Y_R$	X_4, X_5X_6, X_5^2, t	0.9469	0.02122	X_4X_5, X_5X_6, X_4X_6 $X_4^2, X_6^2, X_4X_5X_6$	<0.0005

X_4 = M.C. (%)

X_5 = Shelling ratio

X_6 = Load

(1) = Rate of creep at 0.0005 inch per day

(2) = 100 minutes

(3) = 1 month

Y = Total deflection

Ye = initial deflection

Y_R = recoverable deflection

Dependent Variable	Variables Considered	R^2	Standard Error of Estimate	Variables Deleted	Overall F Significance Level
(3) Y	$X_4, X_5, X_6, X_4X_6, X_5^2, X_6^2, t$	0.9264	0.0795[illegible]	[illegible]	<0.0005
Y-Ye	X_4, X_5, X_6, X_5^2, t	0.9549	[illegible]	[illegible]	<0.0005
Y_c-Y_R	X_4, X_5, X_6, X_5^2, t	0.9469	0.03[illegible]2	[illegible]	[illegible]

deleted variables, and over-all significance level for all nine different expressions.

The regression expressions for the total bending deflection Y(t), total creep deflection Y(t)-Ye, and irrecoverable creep (flow) $Y_C(t)-Y_R(t)$ are given below:

(a) Rate of creep at 0.0005 inch per day:

$$Y(t) = K\left(\frac{0.04574200}{K} + 0.00014939\,X_4 - 0.00382642\,X_5 + 0.00004560\,X_6 - 0.00834455\,X_4X_5 + 0.00030677\,X_4X_6 - 0.0001093\,X_4^2 + 0.00299555\,X_5^2 - 0.00000038\,X_6^2\right) \quad (6)$$

$$R^2 = 0.9920$$

in which $K = A(t-1)^B$ (T, A, B can be derived from short term creep test)

X_4 = moisture contents (per cent)

X_5 = shelling ratio (0.000 - 1.000)

X_6 = load level (lbs)

$$Y(t) - Ye = K\left(\frac{0.01019966}{K} - 0.00000274\,X_4 - 0.00394232\,X_5 + 0.00003625\,X_6 - 0.00168300\,X_5X_6 + 0.00023765\,X_4X_6 + 0.00297272\,X_5^2 - 0.0000027\,X_6^2\right) \quad (7)$$

$$R^2 = 0.9924$$

$$Y_c(t)-Y_R(t) = K(\frac{0.02344107}{K} + 0.00033523\ X_4 +$$
$$0.00039063\ X_5 + 0.00002359\ X_6 -$$
$$0.00002424\ X_4^2 - 0.0000029\ X_6^2) \quad - - (8)$$

$R^2 = 0.9231$

(b) t = 100 minutes

$$Y(t) = K(\frac{0.01702791}{K} + 0.10311864\ X_4 - 0.82665660$$
$$X_5 + 0.03097935\ X_6 + 0.00009820\ X_4X_6 -$$
$$0.0091917171\ X_4^2 - 0.00033957\ X_6^2) \quad - - - \quad (9)$$

$R^2 = 0.9623$

$$Y(t)-Y_e=K(\frac{0.00170190}{K} + 0.00138130\ X_4 - 0.24545878$$
$$X_5 + 0.00333211\ X_6 + 0.17470495\ X_5^2 -$$
$$0.00002683\ X_6^2) \quad - - - - - - - - - - - - - \quad (10)$$

$R^2 = 0.9940$

$$Y_c(t)-Y_R(t)=K(\frac{0.00083221}{K} + 0.01028061\ X_4 -$$
$$0.03730320\ X_5 + 0.00048373\ X_6 -$$
$$0.00058381\ X_4^2) \quad - - - - - - - - - - \quad (11)$$

$R^2 = 0.9646$

(c) t = 1 month

$$Y(t) = K(\frac{0.05346360}{K} + 0.00008669\ X_4 - 0.02970277\ X_5$$

$$+ 0.00011662\ X_6 + 0.00019135\ X_4X_6$$

$$+ 0.01991767\ X_5^2 - 0.00000034\ X_6^2) \quad - - - \quad (12)$$

$R^2 = 0.9264$

$$Y(t)-Ye=K(\frac{0.02454245}{K} + 0.00005838\ X_4 - 0.02259931$$

$$X_5 + 0.00010888\ X_6 + 0.01665380\ X_5^2) \quad - \quad (13)$$

$R^2 = 0.9549$

$$Y_C(t)-Y_R(t)=K(\frac{0.01622968}{K} + 0.00002920\ X_4 -$$

$$0.01615386\ X_5 + 0.00008031\ X_6 +$$

$$0.01218140\ X_5^2) \quad - - - - - - - - - \quad (14)$$

$R^2 = 0.9469$

The values of constant A and B which should be used in making predictions from a regression curve depend on the type of composite, moisture contents and load level involved.

In examination of R^2 values from the above statistical expressions, regressions account for 92 to 99 per cent of the total variations in the above nine different dependent variables. Since the square of multiple correlation coefficient (R) measures the degree of the combined effect of the independent variables on the dependent variables, the reliability of any estimated deflection values which are derived from the above regression equations can be considered extremely good. In all cases, the predicted

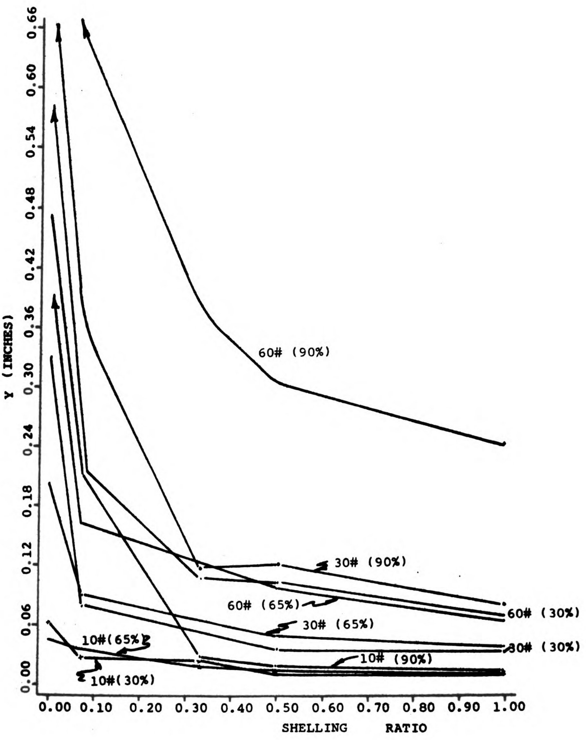
deflection values should correspond reasonably well with the actual experimental results. Therefore, the best approximation of total maximum bending deflection and total creep deflection of a composite furniture panel can be determined by the use of regression equations 6 and 7, as above.

Based on a rate of creep at 0.0005 inch per day and developed multivariable regression equations 6, 7 and 8, the best approximations of total maximum bending, creep and irrecoverable creep deflections are shown in Figures 21, 22 and 23. Under a low constant 10 pound load, total maximum and creep deflections as functions of shelling ratio and relative humidities are shown in Figure 24.

In view of the figures, it can reasonably be understood that all the creep behaviors of approximated total bending and creep deflections were similar to those of the short term 100 minutes creep test results. It should be noted that veneered particleboard composites were, as would be expected, somewhat superior in creep property to the 3/4 inch particleboard. The application of 1/36 inch thin veneers on both sides of the particleboard made the panel at least twice as stiff and reduced the large amount of creep to about half to one third of that occurring in the unveneered board. By further increasing the veneer thickness of the composite panel, creep deflection can be reduced, but at a decreasing rate thereafter. Least creeps

Figure 21.--Total maximum bending deflection (Y) as function of shelling ratio, load level, and relative humidity

(The rate of creep at 0.0005 inch per day)



Y (INCHES)
0.00
0.06
0.12
0.18
0.24
0.30
0.36
0.42
0.48
0.54
0.60
0.66
60# (90%)
30# (90%)
60# (65%)
60# (30%)
30# (65%)
10#(65%)
30# (30%)
10# (90%)
10#(30%)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
SHELLING RATIO

Figure 22.--Total maximum creep deflection as function of shelling ratio, load level, and relative humidity

(The rate of creep at 0.0005 inch per day)

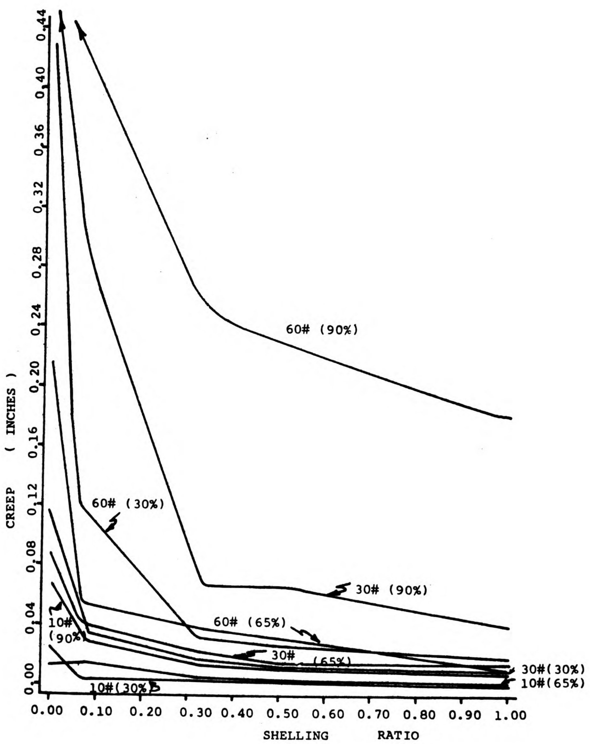

CREEP (INCHES)
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
0.36
0.40
0.44
60# (90%)
60# (30%)
30# (90%)
60# (65%)
10#
(90%)
30#
(65%)
30#(30%)
10#(65%)
10#(30%)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
SHELLING RATIO

Figure 23.--Total flow (irrecoverable creep) as function of shelling ratio, load level, and relative humidity

(The rate of creep at 0.0005 inch per day)

ction
tive

ay)

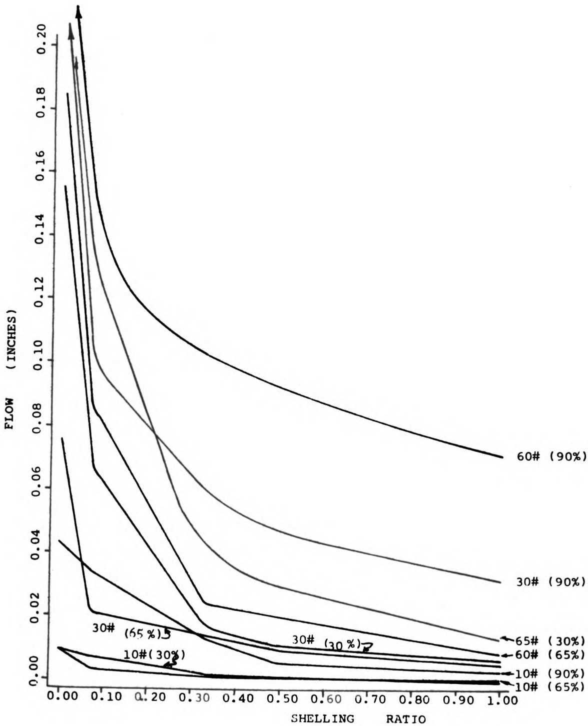


Figure 24.--Total maximum bending and creep deflections as function of shelling ratio and relative humidity

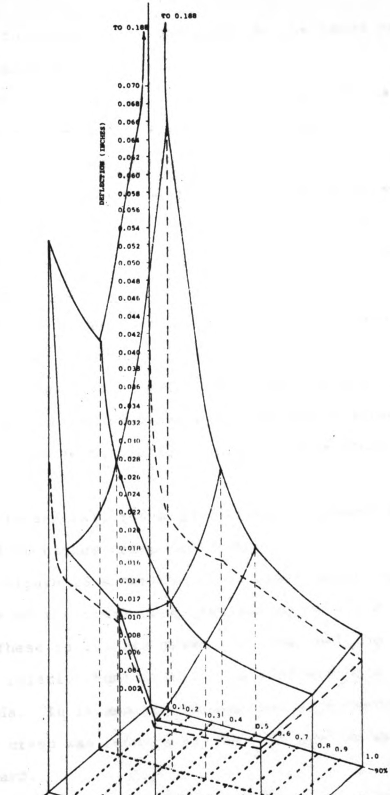
(Under a sustained loading of 10 pounds)

_______ Total deflection (Y)

------- Elastic (initial) deflection (Ye)

Y-Ye = creep deflection

(The rate of creep at 0.0005 inch per day)



TO 0.188
TO 0.188
DEFLECTION (INCHES)
0.070
0.068
0.066
0.064
0.062
0.060
0.058
0.056
0.054
0.052
0.050
0.048
0.046
0.044
0.042
0.040
0.038
0.036
0.034
0.032
0.030
0.028
0.026
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
90%
65%
30%
RELATIVE HUMIDITY
SHELLING RATIO
3/4" Pt. Bd.
1/36"W
1/8"W
3/16"W
3/4"W

[illegible] deflections as [illegible] relative humid-

[illegible] pounds)

[illegible] deflection (Ye)

[illegible]

(The rate [illegible] .005 inch per day) occurred in solid walnut and 3/16 inch veneered particleboard composite.

The results also signify that humidity has a strong influence on the creep behavior of the particleboard composites. As the relative humidity was raised to 90 per cent, the creep effect became sizable, especially in the case of 3/4 inch particleboard. An unusual phenomenon is shown in Figure 23. The irrecoverable creep of all specimens under 30 pound load at 90 per cent humidity was higher than that of the specimens with a constant load of 60 pounds at low to medium humidities.

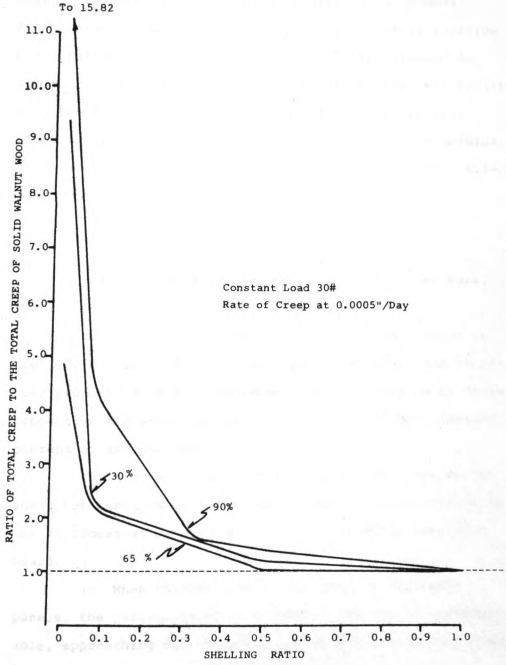
It can also be seen from Figure 24 that the creep deflections of specimens were approximately directly proportional to the initial deflection at any given relative humidity.

In general, the higher initial deflection always resulted in higher creep deflection.

Figure 25 shows the total creep of all specimens in terms of the total creep deflection of solid walnut wood. These ratios are drawn over the shelling ratio for various relative humidities. The load was held constant at 30 pounds. It is amazing to see that a tremendous proportion of creep was reduced by the 1/36 inch veneered particleboard.

The best approximated total relative creep (ratio of total deflection to the initial deflection) results as

Figure 25.--The ratio of total creep to the total creep of solid walnut as function of shelling ratio and relative humidity



To 15.82
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
RATIO OF TOTAL CREEP TO THE TOTAL CREEP OF SOLID WALNUT WOOD
Constant Load 30#
Rate of Creep at 0.0005"/Day
30%
90%
65 %
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
SHELLING RATIO

functions of shelling ratio and humidities are shown in Figure 26. The loads were held constant at 30 pounds. Again, high humidity condition resulted in higher relative creep ratios which were based on the initial elastic deflection. Creep ratios of 30 per cent and 65 per cent didn't show too many differences in terms of shelling ratios; since specimens of various shelling ratios vary in modulus of elasticity, their initial elastic deflections were different at the beginning.

C. Summary of the Results

Based on the reported conditions and tested data, the results can be summarized as follows:

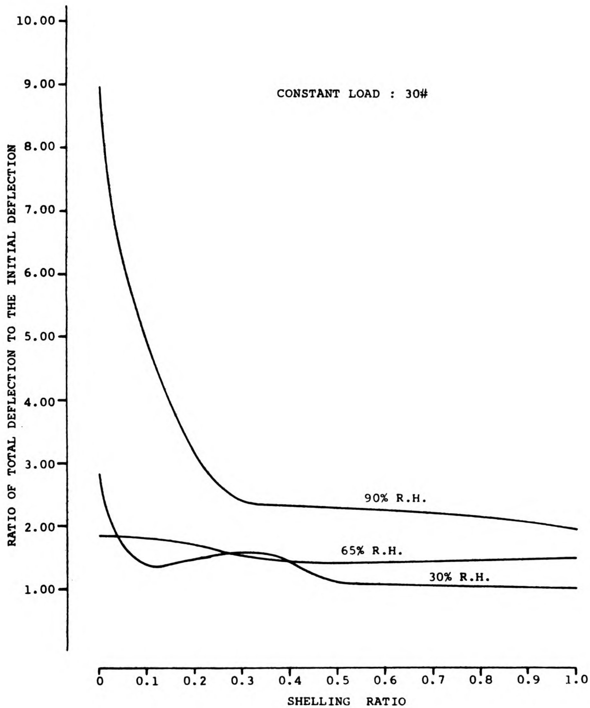
(a) The direct effect of high moisture content is highly significant for both the bending strength and stiffness properties of all specimens. The differences of these properties are small between low and intermediate moisture content of the specimens.

(b) The method of analysis which takes into account shear contribution to deflection is preferred in predicting the stiffness at proportional limit of veneered particleboard.

(c) When thicker veneers are used in composite panels, the percentage of shear deflection can be considerable, approaching the amount of deflection due to pure bending, especially under high humidity condition.

Figure 26.--Relative creep (the ratio of total deflection to the initial deflection) as function of shelling ratio and relative humidity

(Total deflection at a rate of creep of 0.0005 inch per day)



CONSTANT LOAD : 30#
RATIO OF TOTAL DEFLECTION TO THE INITIAL DEFLECTION
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
90% R.H.
65% R.H.
30% R.H.
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
SHELLING RATIO

(d) Particleboard, veneered composites and solid walnut wood are all viscoelastic materials. Their behavior is significantly affected by the reactions to the creep deflection.

(e) The load at the creep limit in bending corresponds to approximately 60 per cent of the load at the proportional limit, or 20-30 per cent of the load at the ultimate bending strength in the static bending test for all specimens of various designs in this study.

(f) By extrapolating the creep data between 10-100 minutes of short term creep tests, the projections were found to be satisfactory to predict the long term creep results in the use of a general form of power law:

$$Y-Y_e = A(t-1)^B$$

in which Y = total deflection

Y_e = initial deflection at 1 minute

t = time in minutes $(10 \leq t \leq \infty)$

A,B = constant

(g) The total bending deflection at a rate of creep of 0.0005 inch per day is considered to be the best practical approximation of total maximum bending deflection for the specimens of various designs in this experiment.

(h) Results of analyses of variance indicate that the initial deflection, creep deflection and irrecoverable deflection of the composite panels are significantly

affected by the independent variables of humidities, shelling ratios, load levels and their interactions.

(i) The best approximation of total maximum bending and creep deflection as functions of shelling ratio, load level, moisture content and time of a composite furniture panel can be made by the use of multiple variables regression equations 6 and 7, both with a R^2 value of 0.99.

(j) The initial elastic deflection and creep deflection are proportionally increased with an increase in the magnitude of the constant load level.

(k) Increasing the moisture content level from approximately 8 per cent to 15 per cent appears to increase the creep deflection and irrecoverable deflection of all specimens for any given load level, particularly in the case of plain particleboard. In some cases, the effect of load level on the creep behavior of the specimens is overshadowed by the effect of high humidity condition.

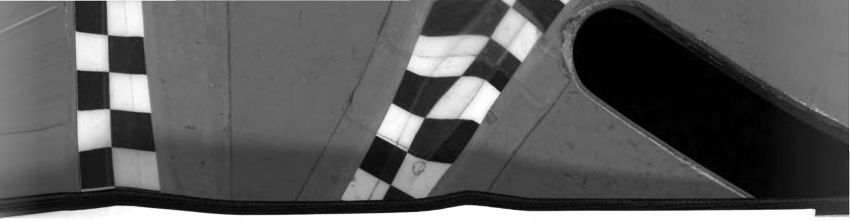
(l) A large amount of creep is reduced by the application of a thin veneer on both faces of the particleboard. After that, the reduction of creep in a composite furniture panel is not proportional to further increasing the veneer thickness.

For instance, the application of 1/36 inch veneer on both faces of particleboard had the effect of making the composite panel at least twice as stiff and reducing the large amount of creep to about half to one-third of that

occurring in unveneered particleboard. It was discovered that a creep performance very close to that of a 3/4 inch solid wood panel can be accomplished by application of 3/16 inch veneer on both faces of a particleboard of 3/8 inch thickness.

(m) To express in terms of a ratio the relationship of total maximum creep deflection in composites to the total creep in solid walnut wood, a ratio of 2.2 was found for the 1/36 inch veneered composite under a practical medium constant load both at low and intermediate humidity conditions, and a ratio of 4.5 was found at high humidity. The ratios for particleboard were much higher, 4.8 at intermediate humidity, 9.4 at low humidity and 15.8 at high humidity. The ratios for 3/8 inch and 3/16 inch veneered composites were all below 2.0 under all humidities.

(n) In no case was recovery such that the test specimen returned to its original shape. However, more than 70 per cent of the creep deflection could be recovered except under high humidity.



VI. CONCLUSIONS

(1) Creep of practical composite furniture panels can be effectively controlled by shelling ratio. Increasing veneer thickness on the particleboard will improve the resistance to creep property. However, from the standpoint of practical and economical purposes, it is impractical to use expensive thick walnut veneers on the particleboard core. A commercial type 1/36 inch walnut veneered particleboard has the effect of reducing a large amount of creep which occurs in an unveneered commercial particleboard, but 1/36 inch walnut veneered particleboard is still inferior in creep resistance to solid walnut wood being one-half as resistant as solid walnut. It is suggested that an economical composite furniture panel with a high shelling ratio and good creep resistance can be made by laminating a cheap veneer between the particleboard core and the expensive thin face veneer such that the grain direction of the cheap veneer is parallel to the grain direction of the face veneer.

(2) Small loads do not cause appreciable creep in the veneered particleboard composite furniture panel. A common explanation that the overhanged (free end) parts of

a veneered particleboard table top or shelf without any load on it may sag or creep under their own weight is not correct. The actual weight of an overhanged part of a table or shelf is too low to create any significant amount of creep to cause the phenomena of visible sagging. This type of sagging must be caused by something other than external load of the panel. One possible reason which causes an unloaded panel to a permanent set is due to unbalanced internal stresses developed in a partially restrained veneered particleboard panel at high humidity.

(3) In addition to taking account of elastic deflection of the panel in designing furniture, creep deflection should also be taken into the consideration of the total bending deflection in designing furniture panels. A rough approximation of the total bending deflection of a 1/36 inch walnut veneered particleboard medium duty shelf may be estimated by multiplying its elastic deflection to a factor between 1.50 and 1.70 under constant dry and normal humidities and to a factor of 5.00 under the constant high humidity condition. However, the best approximation of the total maximum bending deflection of the veneered particleboard composites of various veneer thicknesses, loading and humidity conditions can be accurately obtained by following the newly developed approximation techniques described in Chapters IV and V.

(4) A walnut veneered particleboard book shelf or table top will bend more under constant high humidity condition (90 per cent) than under constant normal humidity condition (65 per cent). For example, with a practical medium loaded shelf in a very damp summer time or on a rainy day, as in an unconditional room, the creep will be about four times as much as at normal humidity of 65 per cent.

(5) A regular 3/4 inch particleboard is only suitable for use in lightly loaded shelves. One-thirty-sixty inch walnut veneered 3/4 inch particleboard composite can be used for medium duty shelves or bookcases. In view of the maximum creep performance standard for the shelves of the kitchen cabinet, 1/36 inch walnut veneered particleboard meets the requirements set by the National Kitchen Cabinet Association (23).

(6) Although this study was undertaken to determine the creep characteristics of walnut veneered particleboard composite under three constant relative humidity conditions, it is believed that the general behavior shown in this study applies as well to combination of mat-formed particleboard core with wood veneers of other species, and other types of facing materials.

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LITERATURE CITED

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