STRUCTURAL COMPOSITE PANEL PERFORMANCE UNDER LONG-TERM LOAD

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Abstract

Information on the performance of wood-based structural composite panels under long-term load is currently needed to permit their use in engineered assemblies and systems. A broad assessment of the time-dependent properties of panels is critical for creating databases and models of the creep-rupture phenomenon that lead to reliability-based design procedures. This paper presents a broad background of information on the creep-rupture phenomenon by describing the microscopic mechanisms of creep-rupture, presenting models commonly used to describe creep deformation and time-to-failure behavior, and reviewing literature on structural particleboards, flakeboards, and plywood. A large test program and future research needs in the field are also described.

Introduction

One property of wood that governs the design of solid wood products is that wood strength is dependent on its time under load (28). Scientists studying this phenomenon have introduced many diverse methods of modeling it. An aspect of the load-duration effect is the time-dependent deformation caused by loads on structural members, which is commonly called creep. Throughout this paper, I will use the term creep-rupture to describe the combined phenomena of increasing deformation and loss of strength with time.

Composite and solid wood products have similar characteristics in regard to the creep-rupture phenomenon. However, because composite products are relatively new to structural uses, their long-term performance history based on common building practices has not been established. Moreover, their rheological properties emphasize the creep aspect of the creep-rupture phenomenon more than the rupture aspect, as is true for solid wood products.

Composite wood products produced from veneers, flakes, strands, wafers, and particles are becoming accepted in structural systems that may have traditionally employed solid wood or steel materials. One reason for this diversity in product application is that these composites can be produced with a wide range of structural properties. Manufacturers can control the production process and thus the short-term strength and stiffness of the products and the variability of their properties.

All wood-based products are susceptible to creep-rupture effects, Thus, inservice stiffnesses must be known and controlled to limit the creep deformation of the wood component and the possibility of rupture in its intended service life. The relative lack of information on creep-rupture in composite materials hinders development of empirical design guidelines such as would be used in a limit-state-type design approach, but it also precludes development of reliability-based assessment. In my view, the format of a reliability-based design approach should set deflection limitations that will simultaneously address serviceability (in this case, deflection) and time to failure under load. This approach will emphasize deflection as the controlling influence in the design of traditional panel products (24).

In this paper, I will provide a background on the creep-rupture phenomenon for composite materials. First, I will describe the macromechanical behavior and the responsible microstructural mechanisms for creep-rupture. I will then provide an overview of past research and current research on creep-rupture. This will be followed by an assessment of research needs for the future.

What is the Creep-Rupture Phenomenon?

The phenomenon of creep-rupture has some very humble beginnings and should be viewed in this way prior to any analytical assessment. From a simplistic standpoint, the deformation of a material under constant load increases over time. As the deformation increases, the material will "fail" at some point. This may take the form of a massive crack in a beam member, a buckled truss component, or simply a floor panel with excessive deflection.

Because I have called the combined phenomena of increasing deformation and loss of strength with time creep rupture, I will illustrate why it is correct to combine them and view this as a continuous process. There are three basic stages in the creep-rupture process: primary, secondary, and tertiary creep, as distinguished by the decreasing, constant, and increasing rates of deformation (Fig. 1). These stages occur in a wide variety of structural materials, including wood-based composites (22).

Some obvious implications from this simple presentation are that (a) the primary phase of creep is a short transition between the elastic (or initial) deformation caused by the load and the steady-state condition represented by the secondary phase, (b) the secondary phase of creep is of widely varying time length and at low loads could be infinite (or nearly so), and (c) the tertiary phase of creep is short-lived and represents the onset of massive fracture of the material.

To justify this view of creep-rupture as a continuous phenomenon requires insight into the microscopic structure of the material. For most wood-based composites, the stresses carried within the material are dependent on such local factors as fiber orientation, species density, and type and content of adhesive. Because of the construction of the composites, some constituents carry larger stresses than others. The highly stressed fibers are the first to release portions of their load through such mechanisms as disbonding, fiber failure, and fiber rotation. These microfailures cause infinitesimal increases in overall material deformation and cause the remaining fibers to be more highly stressed. In addition to these microfailures, wood fibers and adhesive bonds under stress will exhibit microcreep. These continuously increasing deformations represent a stress relaxation of some wood fibers and adhesive bonds that are redistributed within the microstructure. This process of microfailures and microcreep followed by stress redistribution presumably occurs at the general rate indicated by the three creep phases shown in Figure 1. Clearly, the mechanisms of the microscopic processes are different in each type of wood composite, but the scenario, as presented, stays basically the same.

Environmental conditions also confound the creep-rupture process. In simple terms, the changing of temperatures and moisture contents cause the deformation rate to increase. The rate of deformation is dependent on the material itself, the load level, the material volume, and the rate of environmental change. Each of these factors results in a gradient of structural properties, which changes the deformation characteristics of the material under load. The environmental stresses placed on inservice composite products may well be the most difficult effect to quantify in terms of the creep-rupture process.

Characteristics of the Creep-Rupture Phenomenon

Creep-rupture is a continuous deformation phenomenon that may end in catastrophic failure of the material under stress. Past experience provides us with two basic behaviors to model: deformation and time to failure. Models employed to characterize either deformation or time to failure are intended to provide a mathematical description of the behavior for a given environmental condition and a range of loading conditions so that the long-term behavior of a material may be predicted in a variety of structural applications.

Creep Parameters and Models for Deformation

Simple parameters for defining creep deformation are described at any point in time (t) by measuring deformation in constant load creep tests. Two of these parameters are

$$\text{Fractional creep }(t) = \frac{\text{Deflection at time } t}{\text{Deflection after loading } (t=o)}$$

and

$$\text{Creep modulus }(t) = \frac{\text{Stress applied}}{\text{Strain at time } t}$$

Many alternate parameters may be defined for these same quantities. However, numerous models are also applied to generate a continuous characterization of the deformation. Two popular ones are the power law and the linear viscoelastic model. The power-law model is defined as

$$\varepsilon_c = at^n$$

where a and n are constants, ε_c is creep strain, and t is time. The linear viscoelastic model has an unlimited series of mechanical elements:

$$\varepsilon_t = \frac{\sigma}{E_o} + \sigma \sum_{n=1}^{n} \frac{1 - \exp(-t/\beta_i)}{E_i}$$

where
- ε_t is total strain,
- σ stress,
- E_0 elastic modulus,
- E_i elastic modulus of the ith element,
- β_i v_i/E_i relaxation time, and
- v_i viscosity of the ith element.

A broader background on this subject is presented by Schniewind (27) in his review of the rheological behavior of wood-based materials.

Creep-Rupture Time-to-Failure Modeling

The time-to-failure models that have traditionally been applied to composite wood products are of the exponential form

$$S = a + b \log_{10} t$$

where
- S is percentage of static strength,
- a and b are constants, and
- t is time to failure.

Of course, this form is normally applied to data collected under constant steady-state stress and environmental conditions. Of growing interest is the use of more sophisticated models, which are termed damage accumulation models (3, 5) and fracture mechanics approaches (23). Yet to be developed, however, is a model that can link the deformation and time-to-failure processes. A broader treatment of this subject may be found in a review of the world literature by Gerhards (4).

Literature Review

I have divided the pertinent literature on structural composite materials into two categories: creep deformation and time to failure.

Creep Deformation

Fundamental work on the creep and stress relaxation in bending for plywood was reported by

Ranta-Maunus (25). Nearly linear viscoelastic behavior was observed for spruce and birch plywood under steady-state climatic conditions when stressed at allowable levels. Shear deformation of bending specimens was observed to be increasingly nonlinear with increasing moisture content. Tests involving cyclic variation of plywood moisture content under long-term loads were also performed by Ranta-Maunus (26). The use of linear viscoelastic theory and constitutive relations was attempted in modeling the time-dependent deflections of plywood as an orthotropic multilayer plate.

Models for predicting the creep of plywood were investigated by Lyon and Schniewind (16). The three models, one-dimensional elastic, two-dimensional elastic, and two-dimensional viscoelastic, were formulated using the measured constitutive elastic properties and a linear viscoelastic theory.

Lehmann et al. (14) studied the bending creep characteristics of three types of particleboard, structural particleboard, and plywood. A relationship between higher creep resistance and longer flakes was observed. Alignment of flakes on the board face also improved creep resistance. Thirty to ninety percent cyclic relative humidity (RH) was found to produce two to four times the creep deflection produced by constant 65 percent RH conditions (Fig. 2).

Haygreen et al. (7) also studied creep of particleboard and plywood under various humidity regimes. About the same flexural creep was noted for cycling RH between 50 and 70 percent or between 55 and 65 percent (96-h cycle) as for a constant 60 percent RH, but creep was much greater for cycling between 40 and 80 percent RH. On adsorbing from a 50 percent RH condition, flexural creep increased with level of adsorbing RH; creep was much greater at 80 percent RH than at the lower adsorbing levels of RH. Under a concentrated load, panel creep was greater at constant 85 percent RH than for cyclic 50 to 85 percent RH. Linear viscoelastic behavior was reported for loads less than 20 percent of the bending ultimate load.

Hall et al. (6) studied creep of particleboard and plywood as floor panels under concentrated loads while under various humidity regimes. Creep was somewhat greater for cyclic RH between 45 and 65 percent (96-h cycle) than for a constant 50 percent RH and considerably greater for cycling between 45 and 85 percent RH; creep under indoor ambient conditions (temperature range 68 to 90°F, RH range 8 to 80 percent) for 1 year was on the same order as creep under 45 to 85 percent RH cycling after about 400 h. The authors noted that creep of both particleboard and plywood was accelerated during adsorption but leveled off or recovered during desorption. This is consistent with some other studies on particleboard but contrary to studies on solid wood.

Ikeda and Takemura (9) studied the effect of flake length on the creep properties of particleboard. Flakes of 1, 3, 4, and 8 cm were used to make particleboards with 0.50, 0.65, and 0.80 specific gravity. No influence of density on fractional creep was observed in this study. Expressions for creep deformation were of the power-law form, and the parameter a, like Young's modulus, was found to depend on flake length and specific gravity. The parameter n was found to be nearly constant regardless of flake length or specific gravity. An average value was found to be n = 0.29.

McNatt and Hunt (21) conducted creep tests of a thick structural flakeboard and plywood materials designed for use as roof decking. Samples were subjected to design bending loads while in a constant 65 percent RH condition or cycled between 25 and 85 percent RH for 90 days. Constant humidity conditions produced fractional creep of 44 to 69 percent while cyclic conditions produced fractional creep of 145 to 276 percent. Plywood exhibited the least creep. Retained bending strengths and stiffnesses were 74 to 99 percent of control specimens, with no significant difference between the plywood and flakeboard retentions or the constant and cyclic environments.

The reader should note that all creep studies of composite materials encompass a number of test variables, which include type of material, specimen size, loading levels, and test environments, as was highlighted in a review of the creep deformation literature (12). That paper also initiated an effort to standardize test techniques, environmental conditions, and data analysis. The long-term tests represent a significant scientific investment, and, as such, an industry standard test method will reduce costs and allow a database of time-dependent properties to be assembled.

Time to Failure

Bryan (1) undertook an early study of time to failure for two particleboard densities and two adhesive types. Stress levels of 65, 70, 75, 80 and 85 percent of the average bending strength were chosen for the long-term loading. Board density and adhesive type were not found to influence the stress/time-to-failure relationship.

The only published work on time to failure that encompasses oriented strandboard (OSB) and softwood plywood is that by Hoyle and Adams (8). Long-term bending tests were completed at 12 percent moisture content on solid wood, OSB, and plywood at 82, 71, and 66 percent of static strength for selected loading periods. Residual strengths of surviving specimens were determined to provide additional confidence in the stress/time-to-failure data.

Kufner (10) tested bending specimens of eight types of particleboard at several different constant stress levels. Moisture contents were reported between 10 and 12 percent. Tests were completed on specimens parallel and perpendicular to the panel length. Lundgren (15) presented data on the time to failure and strain at failure for tempered hardboard, particleboard, and common fiberboard stressed in tension. Regardless of applied stress and duration of load applied to tempered hardboard, the strain at failure was found to be fairly constant at approximately 0.9 percent elongation.

In a broad study on strength loss of hardboard over time, McNatt (17) evaluated six commercial 1/4-in-thick hardboards with rate-of-loading and constant-load tests. All major modes of loading were assessed using the rate-of-loading tests whereas only tension tests were completed for the constant load time-to-failure tests. Strength losses of 8 percent for each tenfold increase in time to failure were noted for different rates of loading and constant-load levels.

Similarly, constant load bending tests on eight commercial brands of 1/4-in tempered hardboards were reported by Chan (2). A total of 40 tests were completed for each brand, and 5 constant stress levels (30, 40, 50, 60, and 70 percent of static load) were used.

McNatt (18,19) conducted an extensive test program on the creep-rupture behavior of several commercially produced particleboards. The program included rate-of-loading tests in tension, bending, interlaminar shear, and edgewise shear. Tension tests and interlaminar shear tests were conducted for constant load time to failure. Rate-of-loading results showed that bending, tension, and shear strengths decreased 6 to 11 percent for each tenfold increase in time to maximum load. McNatt (20) also tested a variety of laboratory flakeboards in a limited study of rate-of-loading effects in bending and tension and constant-load behavior in tension.

Table 1 summarizes the results of these constant load time-to-failure tests, which illustrate the range of results found in the literature. As with the review of creep-deformation research, the work of many researchers in identifying time-to-failure relationships cannot be directly compared. With variable materials, geometries, loadings, environments, and analysis methods, the best that can be gleaned from the sundry results is an insight into the sensitivity of time to failure to the many variables. Toward this end, I reviewed the time-to-failure data in the world literature, and I have some suggestions on how researchers can help each other by providing some common baselines for further experimental work (13).

Table 1.--SUMMARY OF CREEP-RUPTURE DATA IN THE FORM OF AN EXPONENTIAL MODEL.[1]

Property	Reference No.	Material	Constants a	Constants b
Tensile strength	20	Structural flakeboard	86.4	-7.9
	18	Structural particleboard	84.8	-8.3
	17	Hardboard	80.3	-7.8
	15	Hardboard	83.2	-9.5
Interlaminar shear	19	Structural particleboard	83.0	-8.1
Bending strength	28	Clear Douglas-fir	90.4	-6.3
	8	OSB[2] and plywood	85.1	-7.6
	2	Hardboard	78.2	-6.8
	10	Structural particleboard	80.3	-7.9
	1	Structural particleboard	83.4	-6.5

[1]The form of the exponential model is $S = a + b \log_{10} D$, where S is percentage of static strength, a and b are constants, and D is time to failure in hours.
[2] Oriented strandboard.

Research for Present and Future Needs

One very clear need in creep-rupture research on structural composites is for a consistent baseline of data. Standardized test methods, materials, and analysis techniques are needed to formalize our approaches to the problem, yet provide adequate flexibility to test creep-rupture hypotheses. A cooperative research program has been established that addresses these basic needs. Under the guidance of a task group from the National Forest Products Association, a joint program on composite panel creep-rupture has been established by Forintek Canada Corporation and the U.S. Forest Products Laboratory. The program is being supported by both the Canadian Forest Service and the U.S. Forest Service as well as the Waferboard Association and the American Plywood Association. Although the program is two years old, results are not expected to be published until 1989 (11). Commercially produced plywood, OSB, and waferboard of varying constructions are being tested to identify the variables most influential in the flexural creep and creep-rupture performance of these composite materials. Environmental conditions will be varied for creep tests but held constant for creep-rupture tests. The test program is intended to provide a broad database on the rheological properties and duration-of-load behavior of these structural panel products. This database will then allow us to formulate a test program to generate the data necessary for the development of design stresses.

Regrettably, a number of other needs still remain for the research community. Greater insight into the microscopic and chemical processes responsible for creep are needed to allow us to predict and control the phenomenon. This is especially true for the interaction of stress, moisture content, and temperature. Understanding these microlevel phenomena will most probably facilitate progress on a global model of the effects of load and environmental history, as mentioned previously. We need to know why creep and hence rupture are accelerated in cyclic environments and what microstructural elements contribute to the process. Only with this level of knowledge will we be able to effectively design materials to resist creep effects.

Another rather straightforward need is for the establishment of performance requirements for structural systems and components to provide designers with guidelines for deflection limits under long-term loading conditions. As already discussed, we also need a creep-rupture model that can incorporate loading and environmental histories of structural members. Obviously, both the performance requirements and the creep-rupture model will be useful in reliability analysis of wood structures.

Concluding Remarks

A number of basic concepts on the creep deformation and time-to-failure phenomena are discussed both separately and jointly using the term creep-rupture. The continuous nature of this joint phenomenon is discussed as a microscopic process, which ultimately produces macroscopic failure. Creep-rupture parameters and models are summarized for both deformation and time to failure as a prelude to presenting the literature on structural composite panel creep-rupture.

Included in the world literature is a collection of research studies on creep-rupture meant to solve specific needs, but the results of these studies cannot be incorporated in a single meaningful database. Creep-deformation information is collected in such a diverse manner that I could not provide a useful quantitative summation. However, I have summarized the available time-to-failure information from several sources for structural wood composites.

Lastly, I have provided an overview of a large North American test program that fulfills a basic need for a broad database on structural composite creep-rupture behavior. Several other broad research needs are offered to this audience as an open invitation for additional creative research on creep-rupture for the expanding family of structural composite products.

References

1. Bryan, E. L. 1960. Bending strength of particleboard under long-term load. Forest Prod. J. 10(4):200-204.

2. Chan, W. 1971. The structural properties of hardboard. FPR 195/01, Forest Prod. Res. Lab., Princes Risborough, Aylesbury, Buckinghamshire.

3. Foschi, R. O., and J. D. Barrett. 1982. Duration of load effects in western hemlock lumber. J. Struct. Div., ASCE 108(ST7): 1494-1510.

4. Gerhards, C. C. 1977. Effect of duration and rate of loading on strength of wood and wood-based materials. USDA Forest Serv. Res. Pap. 283. Forest Prod. Lab., Madison, WI.

5. Gerhards, C. C., and C. L. Link. 1983. Use of a cumulative damage model to predict load duration characteristics of lumber. Presented at IUFRO Div. 5 Conf., Madison, WI.

6. Hall, H., J. Haygreen, and B. Neisse. 1977. Creep of particleboard and plywood floor deck under concentrated loading. Forest Prod. J. 27(5):23-32.

7. Haygreen, J. H., K-N. Yang, and R. Sawicki. 1975. Studies of flexural creep behavior in particleboard under changing humidity conditions. Wood and Fiber 7(2):74-90.

8. Hoyle, R. J., and R. D. Adam. 1975. Load duration factors for strand wood, plywood, and clear wood. In Proc. of the 9th Washington State University Symposium on Particleboard, p. 83-109.

9. Ikeda, T., and T. Takemura. 1979. Effect of chip length on creep properties of particleboard. J. of Japan Wood Research Soc. 25(5):332-337.

10. Kufner, M. 1970. Creep in wood particleboard under long-term bending load. Holz als Roh- und Werkstoff 28(11):429-446.

11. Laufenberg, T. L. 1986. Creep and creep-rupture in reconstituted panel products: A cooperative North American study. In Proc. of International Workshop on Duration of Load in Lumber and Wood Products. Special Publication No. SP-27. Forintek Canada Corporation. Vancouver, B.C., Canada. p. 61-66.

12. Laufenberg, T. L. 1987. Creep testing of structural composite panels: A literature review and proposed standard. In T. M. Maloney, ed., Proc. 21st International Particleboard/Composite Materials Symposium, Washington State University, Pullman, WA. p. 297-313.

13. Laufenberg, T. L. 1988. Composite products rupture under long-term loads: A technology assessment. In Proc. 22nd International Particleboard/Composite Materials Symposium. Washington State University, Pullman, WA. (In press)

14. Lehmann, W. F., T. J. Ramaker, and F. V. Hefty. 1975. Creep characteristics of structural panels. In Proc. of the 9th Washington State University Symp. on Particleboard. p. 151-172.

15. Lundgren, S. Ake. 1957. Hardboard as construction material--a viscoelastic substance. Holz als Roh- und Werkstoff, 15(1):19-23.

16. Lyon, D. E., and A. P. Schniewind. 1978. Prediction of creep in plywood. Part I. Prediction models for creep in plywood. Wood and Fiber 10(1):28-38.

17. McNatt, J. D. 1970. Design stresses for hardboard--effect of rate, duration, and repeated loading. Forest Prod. J. 20(1):53-60.

18. McNatt, J. D. 1975. Effect of rate of loading and duration of load on properties of particleboard. USDA Forest Serv. Res. Pap. FPL 270. Forest Prod. Lab., Madison, WI.

19. McNatt, J. D. 1978. Stress-rupture of particleboard in interlaminar shear. Forest Prod. J. 28(9):34-36.

20. McNatt, J. D. 1985. Rate and duration-of-load behavior of lab-made structural flakeboards. USDA Forest Serv. Res. Note FPL-0252. Forest Prod. Lab., Madison, WI.

21. McNatt, J. D., and M. 0. Hunt. 1982. Creep of thick structural flakeboards in constant and cyclic humidity. Forest Prod. J. 32(5):49-54.

22. Nielsen, A. 1972. Rheology of building materials. Document D6. National Swedish Institute for Building Research, Stockholm 27, Sweden.

23. Nielson, L. F. 1986. Wood as a cracked viscoelastic material. In Proc. of International Workshop on Duration of Load in Lumber and Wood Products. Richmond, B.C., Canada. Special Publ. No. SP-27. Forintek Canada Corp., Vancouver, B.C. p. 67-89.

24. O'Halloran, M. R., J. A. Johnson, E. G. Elias, T. P. Cunningham, Jr. 1988. Consideration of reliability-based design for structural composite products. Forest Prod. J. 38(4):35-43.

25. Ranta-Maunus, A. 1972. Viscoelasticity of plywood under constant climatic conditions. Report No. 3, State Inst. Tech. Res., Helsinki.

26. Ranta-Maunus, A. 1973. Deformations in plywood structures caused by long-term loading. Paper Och Tra 1(1):15-22.

27. Schniewind, A. P. 1968. Recent progress in the study of the rheology of wood. Wood Sci. Technol. 2(3):188-206.

28. Wood, L. W. 1947. Behavior of wood under continued loading. Eng. News-Record 139(24): 108-111.

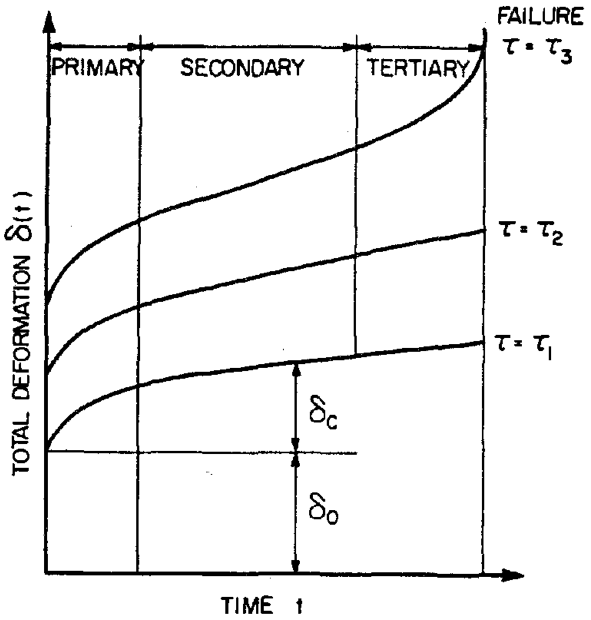

Figure 1. Idealized elastic (δ_0) and creep (δ_c) deformation as a function of time for three stress (τ) levels in a material. Only the $\tau = \tau_3$ curve shows all three stages of the creep-rupture process, which ends with an excessive deformation.

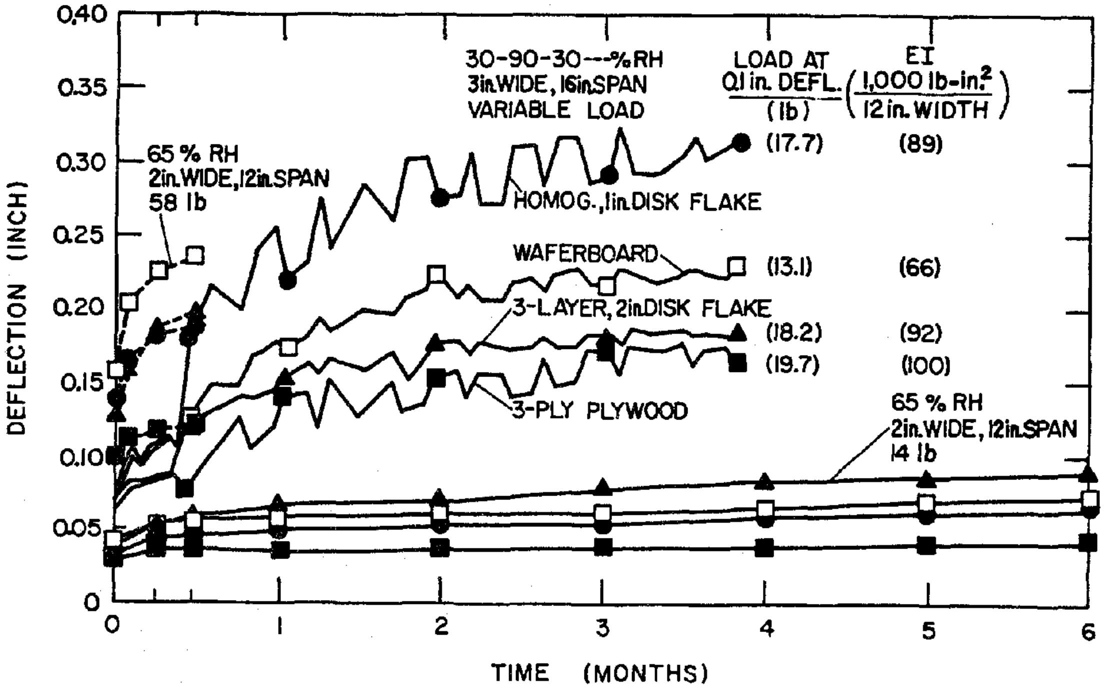

Figure 2. Creep deflection of four panel types under three load and exposure conditions. Numbers in parentheses indicate load and stiffness (EI) for specimens in the cyclic environment. Note that cyclic conditions (30 to 90 percent relative humidity (RH)) produced two to four times the creep deflection of a constant condition (65 percent RH). (M 143 311)

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