MATERIAL VARIABILITY AND WOOD JOIST FLOOR RESPONSE

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ABSTRACT

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An investigation of how the variability of floor component material stiffnesses affect the response behavior for wood joist floor systems is presented. The study considered floors sampled from several combinations of specified Weibull distributions for joist and plywood modulus of elasticity and/or slip modulus variations. Their effects on the deflection, joist tensile stress and nail force response behavior was evaluated. The results from the Monte-Carlo simulations, which included groups of 25 floors, were used to obtain linear approximations of the influence of material variability on both mean maximum floor response and the maximum response variability resulting with uniform and concentrated loadings. The effect of plywood joint conditions, plywood thickness, and the addition of particle board and oak flooring third layers on the response of floor systems are also reported. Simulations of some common U.S. design code minimum floor configurations and requirements incorporating different combinations of material variabilities, including some considering an among-mill and within-mill sampling procedure, were conducted. The behavior of these minimum floors is discussed. The beneficial effects of structural interaction and the detrimental effects of component variability were both included in this simulation study which utilized a finite element formulation to analyze the multilayered partially composite floor systems. The simulated results and the results obtained by considering the joist component only in response calculations were compared and were shown to differ greatly. Inclusion of both component variability and

structural interaction are needed to accurately predict the response of wood joist floor systems.

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The reported research is a portion of a continuing program being conducted in the Departments of Civil Engineering and Forest and Wood Sciences at Colorado State University which has the goals of better defining the behavior of composite wood structures such as wood joist floors, the development of proper procedures for the analysis of such systems, and the adoption of these analyses to the design of such structures so that better and more economical housing can be provided. Results from several previously completed and concurrent phases of this overall effort were invaluable in accomplishing the research reported in this volume.

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INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

The design and construction procedures for engineered structures, including those utilizing renewable natural resources, should allow the structure to benefit from the interaction of all of its components. To accomplish this in the design usually requires the use of a sophisticated analysis technique. The resulting design should be economical and safe.

The current design of wood joist structural systems, such as those found in residential housing, is primarily based on a simplifying assumption of independent structural component action (1, 2).*

Many years of experience has demonstrated that this method of designing results in adequate and safe structures (3).

Material property variations should be incorporated into any realistic analysis technique when these variations can be sizeable. For wood joist floor systems, Dawson (4, 5) has shown that large joist modulus of elasticity (E) variations can occasionally result in the predicted deflections higher than the results from a joist only calculation using an average E value predicts, although most joists will deflect much less than this amount. Dawson (4, 5) has shown that as the variation of joist E increases, the mean maximum deflection also increases. The effects of variations in the properties of other structural components such as plywood, flooring and the appropriate connector slip modulus values, as well as a more general study of the effect of variations in wood joist E, on the response of wood joist floor systems have not been investigated.

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*Numbers in parenthesis refer to entries in bibliography.

Designing with structural efficiency can be obtained when the variation of component properties and component interaction are jointly considered. To demonstrate this efficiency and to further answer the question of how component variability affects floor response, additional Monte-Carlo simulation studies have been conducted using a previously developed finite element formulation for analyzing multilayered wood joist floor systems which incorporates incomplete composite two-way action.

1.2 Objective

This study is a part of a larger research effort on wood joist structural systems underway at Colorado State University and was sponsored by the National Forest Products Association and the National Science Foundation. This study has the following three objectives:

The primary objective was to determine the effects material property variability have on the response of a basic uniformly loaded floor system. This study was primarily concerned with joist deflections and tensile joist stresses resulting from variability of joist E, sheathing E and slip modulus values.

The second objective was to examine the change in the basic floor response caused by changes in geometric conditions such as sheathing joint conditions (tongue and groove versus butted), loading (uniform versus concentrated) and sheathing thickness.

The third objective was to predict the response of selected uniformly loaded floor systems having minimum common floor member sizes and configurations allowed by the Federal Housing Administration of the Department of Housing and Urban Development. Both single population distributions and populations including among and within mill variations have been considered.

1.3 Literature Review

Simulations of structural behavior and reliability studies have been of recent interest as a means of predicting wood joist floor response.

Zahn (6) analytically studied some of the effects on structural response arising from variability in the strength characteristics of wood joist floor components. He noted that the consequences of these variations could be lessened by considering the load sharing existing among the joists. The structures considered by Zahn in his analyses included an arbitrary number of joists and a single narrow deck element crossing the midspan of the joists at right angles. Failure models considered for this structure were the weakest link model, where every member carries the same load (no load sharing), the brittlest link model, where every member undergoes the same deflection (complete load sharing), and a flexible deck model.

Zahn experimentally obtained modulus of rupture (MOR) data for four lumber grades and using these data analytically obtained MOR distributions for the weakest link and brittlest link models. The MOR distribution for the flexible deck model was obtained by computer simulation.

From results obtained using a five joist structure with the weakest joist in the center, Zahn concluded that with his structure and variabilities the greatest minimum increase in load capacity as a result of load sharing is twelve percent obtained by the difference in the weakest link and brittlest link models.

Bonnickson and Suddarth (7) conducted a study on load sharing ability of a wood structural system and the reliability of this load sharing. The reliability of a single joist was compared with that expected for a beam consisting of three joists laminated vertically. Structural reliabilities were obtained for each group from load probability distributions. The MOR values for the laminated three joist system were averaged to obtain an MOR value for the single laminated beam. It was found by comparing the response of the one joist and the three joist system that the reliability and load carrying capacity of both systems is dependent upon the loading condition. For light concentrated loading conditions the triplet system had a higher reliability and as a result lower coefficients of variation in average strength.

Suddarth, Woeste and Yao (8) reported the use of a Monte-Carlo simulation analysis to determine the mean deflection of two simple structures. The structures considered were an axially loaded wall stud (pinned at one end) and a three member truss where each member was pinned to a support at one end and joined to the other two members at the other end with angles of 0, 30 and 60 degrees measured from the base. The modulus of elasticity was the independent variable for both of these structures. A lognormal distribution with a specified coefficient of variation (COV) was used to describe the population distribution for the stiffnesses of the components in each structure. Ten-thousand structures with randomly selected member E values were generated. Deflections were then computed for each structure. From these results a mean deflection value and COV was obtained. Closed form theoretical deflection distributions and those obtained with the Monte-Carlo simulations were in good agreement.

Dawson (4), in 1974, reported the use of the Monte-Carlo simulation technique to study the effect of joist E variability on the behavior of wood joist floors. Analysis of his simulated floor structures were performed using a mathematical analysis model developed at Colorado State University (2, 9) and verified by Liu (10).

Cumulative joist E distributions in Dawson's work (4) were defined by using a Weibull distribution (11) function and three levels of COV. The lowest coefficient of variation value was 5.6 percent. The medium coefficient of variation value was 20.4 percent and the highest COV value of 40.8 percent. Three floor configurations were considered. The first included 160 inch long nominal 2 by 8 inch joists with a single sheathing layer of 3/4 in. thick plywood nailed 8 inches on center with 8d nails. A constant slip modulus of 30,000 pounds per inch (pli) (12) was assumed. An analytical model using a finite difference solution method was used. The second floor was the same as the first except for the substitution of 1/2 in. thick plywood and a connector slip modulus of 15,000 pli. The third floor was the same as the first and was analyzed using a finite element formulation for the mathematical model. All floors were analyzed for an assumed uniform load of 40 pounds per square (psf) foot. Each of the three COV values were studied for each floor.

Results from all three simulations showed a slightly nonlinear relationship between the COV of the joist E and the mean maximum values of the joist deflections within each floor. The mean of these maximum deflections within each floor increased about 18 percent for a joist E variation of 40.8 percent. For both the second and third basic floor types, use of high joist E variability (40.8 percent) resulted in a mean of the maximum deflection within each floor greater than span/360. This increase in deflection was attributed to the open gap separating the plywood sheets. The deflection COV was found to be linearly related to the joist E COV. In all simulations the mean maximum deflection and its COV both increased as the joist E COV was increased. Dawson demonstrated that the use of Monte-Carlo simulation techniques were economical and obviously much less time consuming than the actual building and testing of full scale floors.

Kameda and Koike (13) incorporated the Monte-Carlo simulation technique in a complex mathematical model of reliability of deteriorating metal structures. Deterioration was defined as damage to structural members resulting from the application of a large load which the structure successfully resisted. Random (both magnitude and duration) repeated loads were used in this study. Their mathematical model could be used to evaluate residual resistance after known loads had been applied. The model could also predict the probable resistance after a future random load. The authors (13) also showed that higher loading COV results in greater deterioration and COV of this deterioration.

The literature cited shows that simulations can effectively be used to evaluate probable structural response due to changing component properties.

To perform a sophisticated analysis of highly indeterminate structures such as a layered floor system, theories of behavior, component relationships and response prediction methods (mathematical models) must first be developed.

Goodman (14) in 1969 presented a consistent small deflection theory for layered wood beams with interlayer slip. He showed through testing of multilayered nailed and partially glued beams that the load-deflection response is generally nonlinear. Excellent agreement was obtained between theoretical and observed test results for both nailed and partially glued systems. In both systems, the deflection could be predicted from a two-term equation consisting of a solid beam result plus an additional deflection term involving the slip modulus, connector spacing, layer dimensions and axial forces.

More recently, Vanderbilt, Goodman and Criswell (2) and Thompson, Goodman and Vanderbilt (9) have presented the theory and formulation of a finite element mathematical model for the analysis of layered wood systems. This formulation in computer program form was used as the analysis method throughout this study. The derivation of the governing differential equations and a flow chart of this model is presented in Section 2.1 of this study.

The above cited literature shows that the interaction of the various components of wood structures can significantly reduce the deflection response of the system. Changes in the component properties have been shown to influence the resulting structural response. Analysis methods for the multilayered floor system have been developed which have been shown to give close agreement with test or theoretical results. The existence of such analysis methods is necessary to allow the floor characteristics to be studied using Monte-Carlo methods.

Chapter II

MATHEMATICAL MODEL AND THE MONTE-CARLO METHOD

2.1 The Mathematical Model

The mathematical model used in this study and its verification has been presented in detail by Vanderbilt, Goodman and Criswell (2), Liu (10), and Thompson, Goodman and Vanderbilt (9).

An important component of the floor model is the analysis of layered beam systems with incomplete composite action. In the floor system the sheathing forms the flange of a multilayered T-beam having the joist as the stem portion. The T-beam system has been studied by Ko (15) and Kuo (16) using linear theory. A T-beam study with nonlinear slip modulus was done by Tremblay (17). A finite element formulation of the linear model has been developed (9) to facilitate the solution of problems described by the floor model.

Assumptions used in the mathematical model for the layered beam include:

1. Linear elastic materials,
2. Small deflections,
3. Negligible shear deformation,
4. Linear strains over the depth of each layer,
5. Linear slip modulus,
6. Negligible friction between layers, and
7. Each layer is bent to the same radius of curvature.

The layered floor system is somewhat simplified in the mathematical model by assuming it can be represented by a set of crossing beams; T-beams in the direction of the joists and sheathing strips perpendicular to the joists (Fig. 2.1). This simplification is possible because the

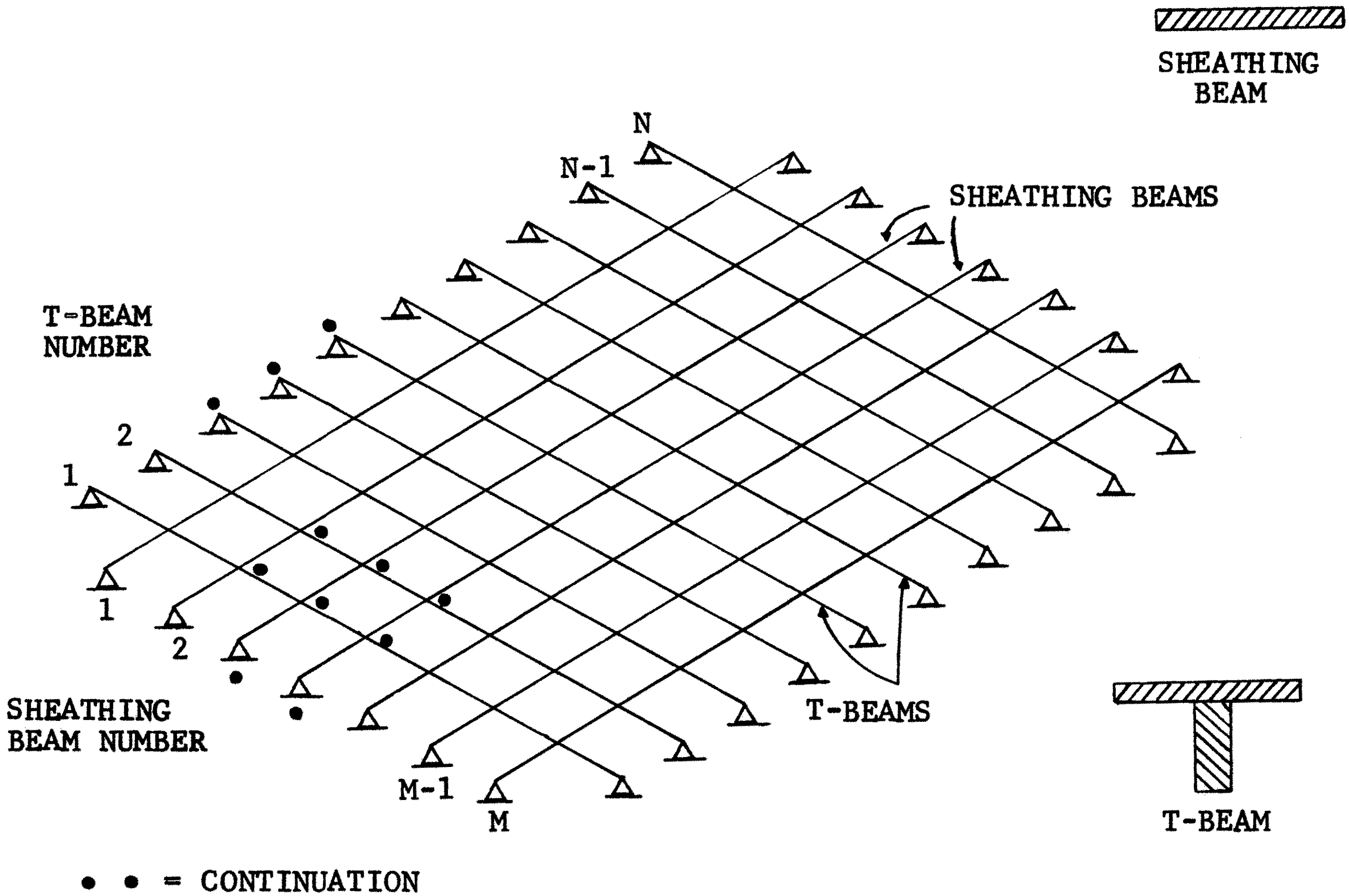


FIGURE 2.1

IDEALIZATION OF A FLOOR SYSTEM

stiffness in the direction of the T-beams is usually much greater than in the sheathing strip direction. The torsional plate stiffness neglected in the crossing beam model is a small contribution to the floor stiffness under these conditions.

Each set of beams is treated as a layered beam system. The deflection behavior of this system can be related to the applied loads through consideration of potential energy from four types of sources:

1. Pure bending of each layer,
2. Axial elongation of each layer,
3. Interlayer slip, and
4. External loads.

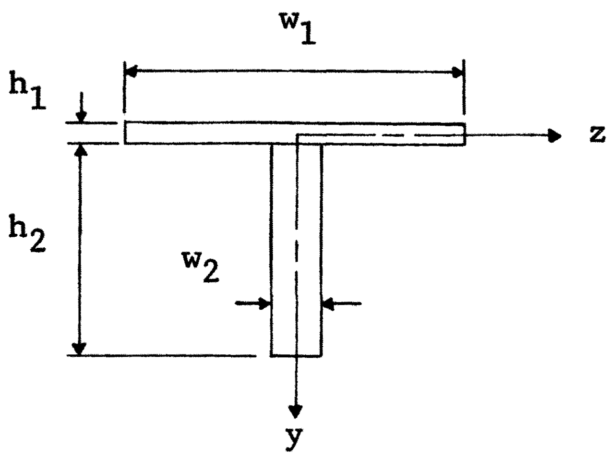
For the two-layered beam system with the notation shown in Fig. 2.2 and using the assumptions of the mathematical model, the curvature of each layer of the beam element can be written as:

$$\frac{d^2y}{dx^2} = \frac{-M_i}{E_i I_i} \tag{1}$$

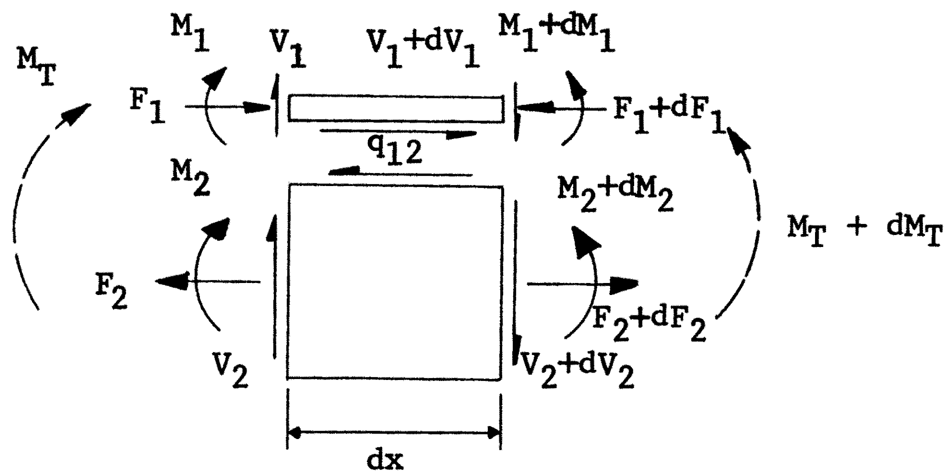
where I_i is the transformed moment of inertia of the ith layer, M_i is the moment in the ith layer, and E_i is the modulus of elasticity of the ith layer. The first governing differential equation for the layered beam system is obtained from the three equations of equilibrium for the beam element of Fig. 2.2b. These equilibrium equations yield, when Eq. 1 is substituted in, the following differential equation:

$$\frac{d^2y}{dx^2} = \frac{-M_T + (h_1 + h_2)\ F}{\Sigma E_i I_i} \tag{2}$$

A second equation can be formulated from requirements relating the interlayer slip and the shear flow between the layers with the characteristics of the nonrigid connectors between layers:



(a) CROSS SECTIONAL DIMENSIONS



(b) FORCE COMPONENTS OF A BEAM ELEMENT

FIGURE 2.2

LAYERED BEAM SYSTEM

$$\Delta S_{ij} = (\frac{s}{kn})_{ij}\ q_{ij} \tag{3}$$

where ΔS_{ij} is the interlayer slip (14), q_{ij} is the interlayer shear flow evaluated by considering horizontal equilibrium, n is the number of connectors per row, k is the slip modulus of the connector and s is the spacing of the connector.

Strains of the individual layers can be evaluated using elementary mechanics of solids equations for stresses and strains arising from moments and axial forces. Using these strains, the interlayer slip can be expressed as the difference between the integral of the top layer strains minus the bottom layer strains. Using the strains obtained from mechanics of solids for a differential slip element, the second governing differential equation can be expressed as follows:

$$\frac{s}{kn}\frac{d^2F_i}{dx^2} = (\frac{1}{E_iA_i} + \frac{1}{E_jA_j})\ F + \left(\frac{h_1+h_2}{2}\right)\frac{d^2y}{dx^2} \tag{4}$$

where F_i is the axial force in the ith layer, h_1 and h_2 are the heights of the two layers and A_i and A_j are the cross sectional areas of the two layers.

The first step in the finite element formulation of this method is to divide the idealized beams into a series of one dimensional elements. The potential energy of the beam is the sum of the energies of all the beam segments or elements. For the proper floor deflection configuration, equilibrium must be satisfied or, alternatively, the variation of potential energy must be zero for each beam.

A further and more indepth discussion of the finite element formulation is presented by Liu (10) and by Thompson, Goodman and Vanderbilt (9). The main steps and basic logic of the finite element solution technique used are displayed in Fig. 2.3.

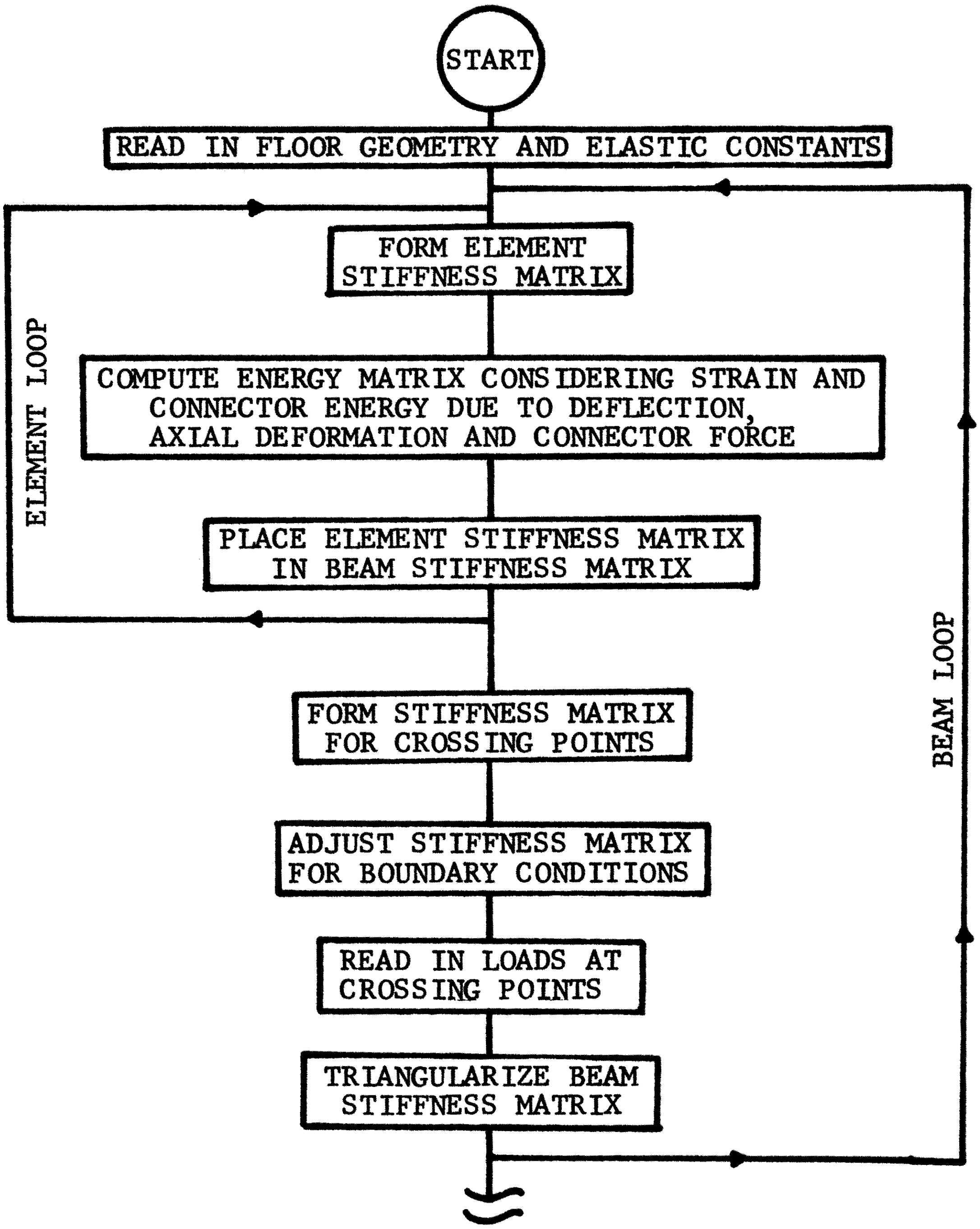


FIGURE 2.3

FINITE ELEMENT FORMULATION FLOW CHART

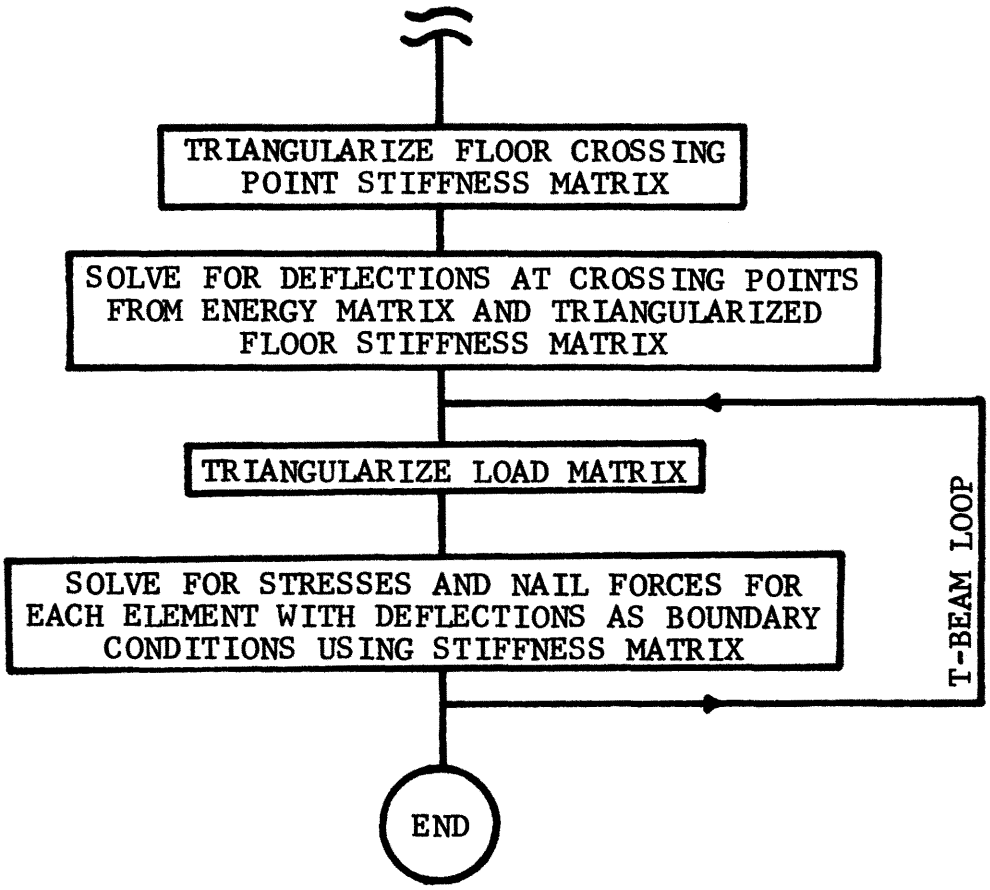


FIGURE 2.3 CONTINUED

2.2 Monte-Carlo Simulation of Floor Response

Determination of the probabilistic response of a highly variable structural system such as wood joist floors through derivation of a closed form statistical analytical solution would be, at best, a complex and time consuming task. For systems with many variable components such as wood floors a closed form solution is not practically possible. The simplicity of the Monte-Carlo method and the ease which with it can be adapted to computer operations gives it the capability of being a powerful research tool in studies to determine the predicted response characteristics of variable systems.

The Monte-Carlo method as used in this study is defined by Hammersley and Handscomb (18) as a method of statistical trials during which computational problems are solved using a random process. A simple example of this method is to roll a pair of dice, with numbers one through six on each, many times and from the results, compute an estimate of the probability that a certain sum, such as seven, will occur.

The random material values used in this study were described by Weibull distributions (4, 11, 19) of a specified mean and coefficient of variation. A typical Weibull distribution is shown in Fig. 2.4. The distribution and the values of its parameters were chosen to simulate realistic material values. The realistic values were obtained from the Colorado State University Wood Science Laboratory (19, 21, 22), the National Design Specification (1), and the Plywood Design Specification (20).

The Weibull distribution is well suited for representing highly variable quantities and skewness characteristics found in the distribution of some wood properties. Weibull distribution coefficients were

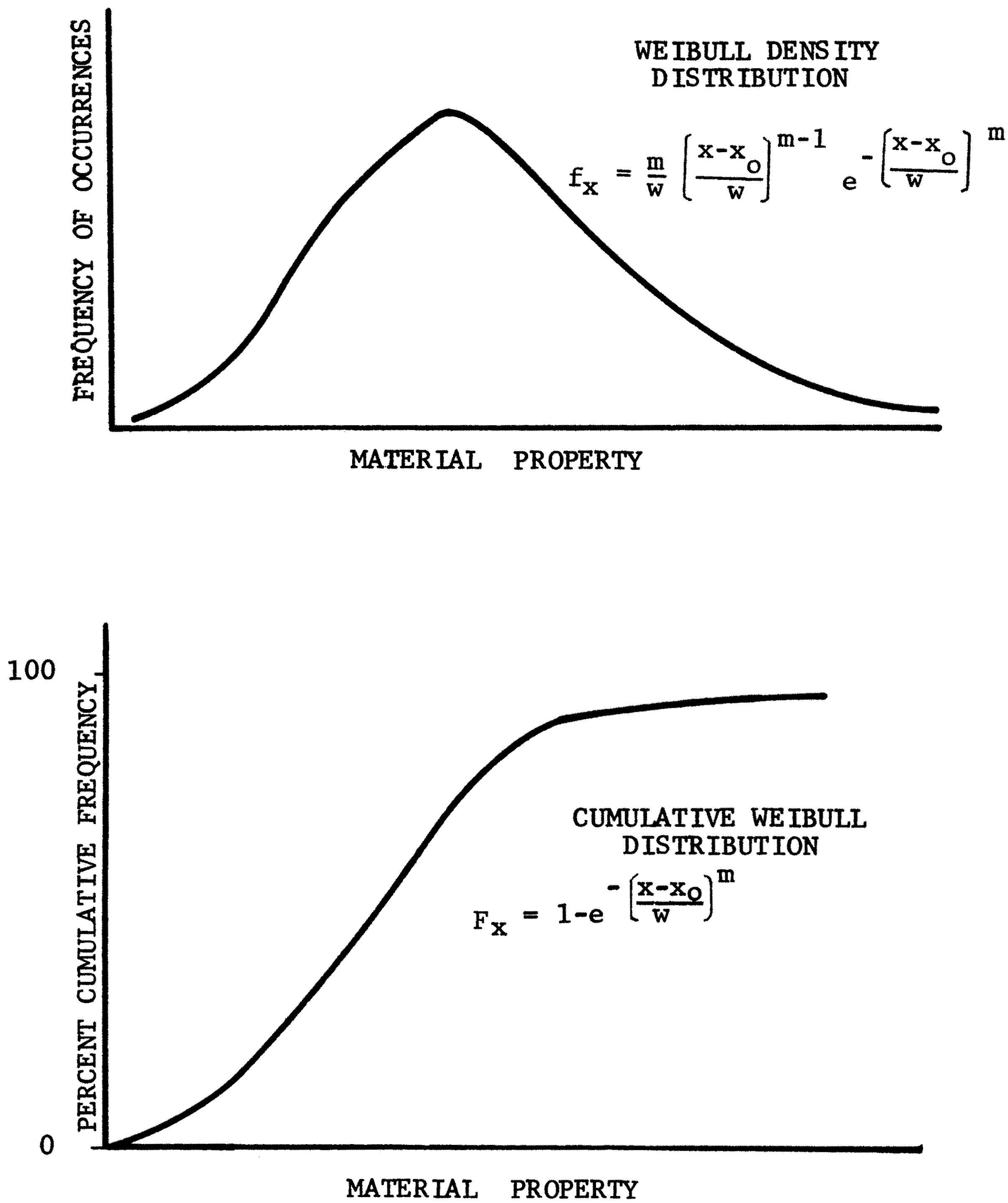


FIGURE 2.4

THE WEIBULL DISTRIBUTION

obtained by a least squares curve fit method discussed by Dawson (4, 5). The adjustments of the Weibull distributions to obtain distributions providing prespecified mean values and COV was accomplished using a linearly changing multiplier computed from the ratio of provided to desired mean values and a variable adjustment, to be discussed in detail by DeBonis (19).

In the simulations, material properties for each floor were obtained using random numbers between zero and one generated within the program. The material property value corresponding to each random number was found by computing the value having a cumulative distribution frequency equal to the random number in percent. For example, for a random number of 0.6215, the value entered for the material property value would be the value expected to be exceeded by 37.85 percent (1.0-0.6215) of all samples. A verified system library function for the Colorado State University CDC 6400 computer was used to generate the random numbers used in this study. The random number generator is a linear congruential type with a modulus of 2^{48} and an increment of zero. The output of the random number generator can be expressed by the following equation:

$$X_{n+1} = (aX_n) \bmod 2^{48} \tag{5}$$

This equation has the capability of generating 2^{48} nonrepeating random numbers as indicated by the mod 2^{48} value given.

To perform the simulations carried out in this study, the previously described and verified finite element formulation of the wood joist floor model was adapted to facilitate solutions of both single and multivariant analysis problems. As shown in Fig. 2.5, this floor

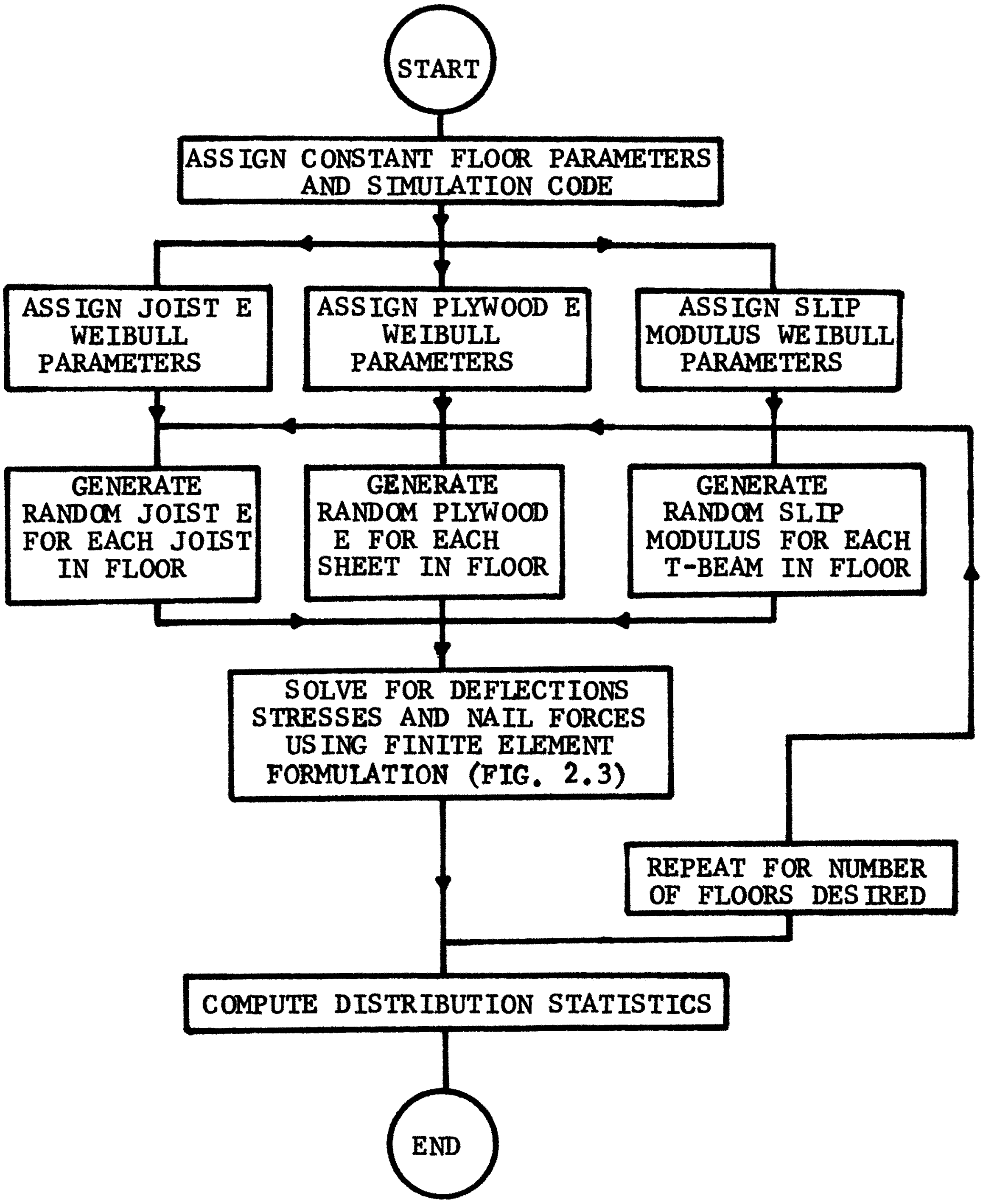


FIGURE 2.5

MONTE-CARLO MULTIVARIANT SIMULATION FLOW CHART analysis formulation was used to determine the response of each floor after the properties of the floor had been defined. Results from all the floors generated from a common set of requirements were then studied to determine the response characteristics. The simulation method is capable of considering any combination of the following characteristics:

1. Different E values for each joist or for each floor,
2. Different E values for each plywood sheet or for each floor,
3. Different slip modulus values for each T-beam or for each floor,
4. Among and/or within mill variations for joist E, plywood E and/or slip modulus, and
5. Two or three layered floor systems, (joist plus one or two layers of sheathing).

Among mill variation recognizes that the mean values of material properties will not be the same for all mills. Among mill variation is introduced by determining through random sampling the mean value produced by the mill supplying the material for the floor. The distribution of material properties within the individual floor is then selected using within mill variation parameters and the assigned mean property value.

Chapter III

EFFECTS OF MATERIAL PROPERTY VARIATIONS ON THE RESPONSE OF A BASIC FLOOR SYSTEM

3.1 Selection of the Basic Floor and Levels of Material Variation

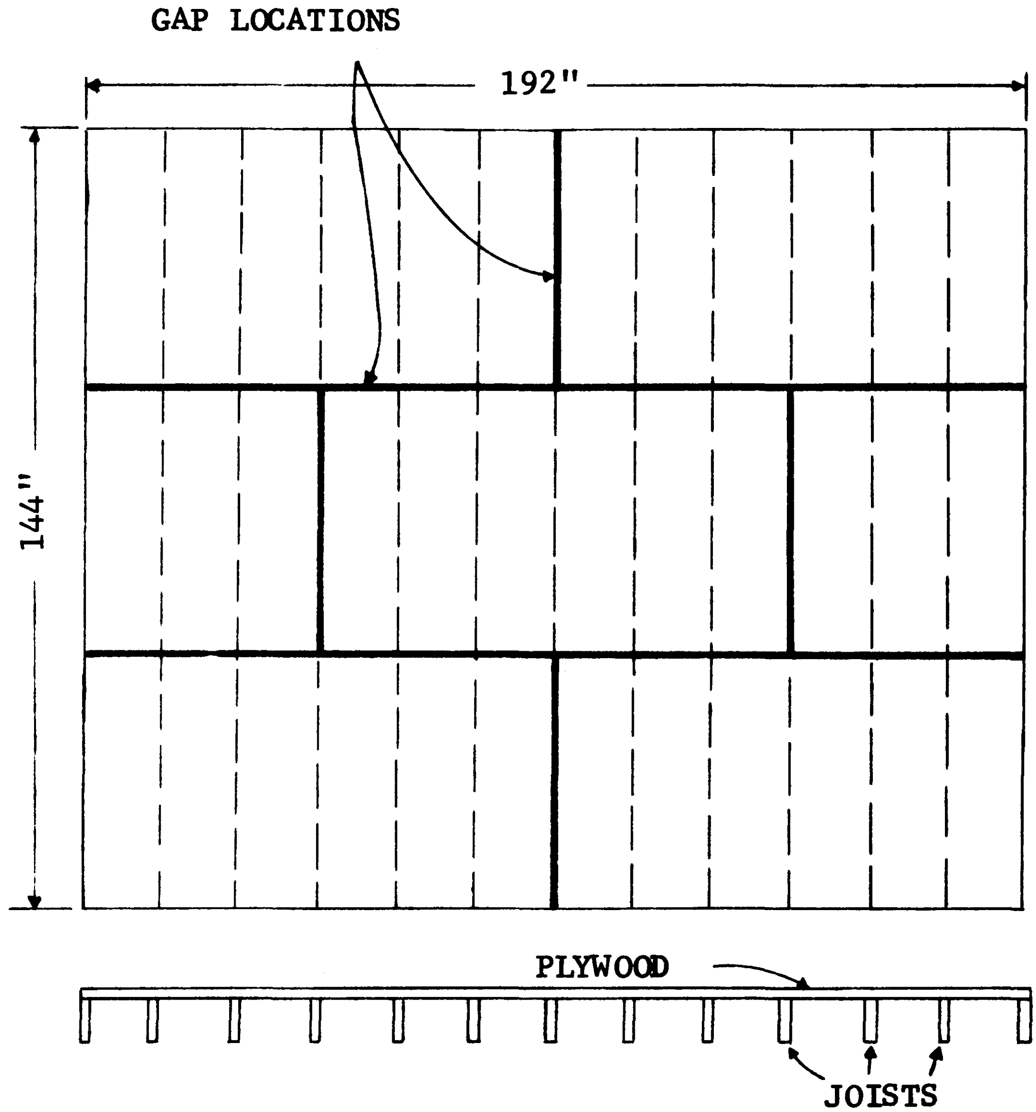
The simulation studies were begun by the selection of a basic floor system. This was used to study the effects of several levels of variability in the properties of one or more floor components and thereby quantify the relationships between member property and floor response variability. The choice for this basic floor is shown in Fig. 3.1. The basic floor consists of nominal 2 by 8 in. joists 12 ft long and 3/4 in. thick tongue and groove (T&G) 4 x 8 ft plywood sheets with tightly butted joints. Eight penny nails were assumed to be speced at 8-in. intervals along the joists spaced at 16-in. centers. The reasons for choosing this particular floor pattern, dimensions and materials were:

1. It geometrically agrees with floors previously constructed and tested at Colorado State University.
2. The 3/4 in. dimension of the tongue and groove plywood results in the floor response being more dependent on plywood properties then if a thinner or a butted plywood was used. Because the influence of plywood variability was expected to be small relative to the effect of the joist modulus of elasticity (E) variability under uniform loads, it was deemed advantageous to exaggerate the effect of the plywood variability slightly so that the characteristics of its effect on floor response would be more visible.
3. Thick plywood allows higher slip modulus values to be used and therefore magnifies the effect of slip modulus variation on floor response.

To evaluate the effect of the variability of different floor component stiffnesses such as joist E, plywood E and slip modulus, simulations were run with only material or connector property varied at a time in order to best isolate the influence of each component variability. The choice of mean values and COV specified for the individual simulations are shown in Table 3.1. The mean property values were obtained after consultation with the Wood Science Department at Colorado State University (19, 21) and reflect results available for properties of Douglas-fir materials. The COV values used are rounded values which were chosen to include the range of values reported by McLain (21), Patterson (22) and Dawson (4). Plywood E values conformed to those expected for standard interior grade plywood. The mean joist E corresponds with that of No. 1 grade Douglas-fir material.

In the random selection of individual property values for the components varied, cutoff values were established to avoid assigned properties values which were felt to be unrealistic and which would result from the occasional sampling from the extremities of the Weibull distributions. Lower and upper cutoff values for joist E were set at 600,000 and 3,500,000 psi. Plywood E parallel to the face veneer and slip modulus cutoff values were set at two standard deviations above and below the mean value. Computed values outside of these cut-offs were replaced with the value at the cutoff point.

In all simulations involving a variable slip modulus, the slip modulus was assumed to be independent of the joist E and plywood E. This assumption was used, even though McLain (23) reported that some degree of correlation over a wide range of material E values exists between the slip modulus and the properties of the members connected.



NOMINAL JOIST DIMENSION = 2x8 in.
NAIL SPACING = 8 in.

FIGURE 3.1

BASIC FLOOR CONFIGURATION

TABLE 3.1 Basic Floor Property Variations

Simulation Number	Mean Joist E PSI x 10^{+6}	COV Joist E Percent	Mean Plywood E*, PSI x 10^{+6}	COV Plywood E, Percent	Mean Slip Modulus lbs/in.	COV Slip Modulus Percent
1	1.800	10.0	1.360 ⊥⊥ 0.529 ⊥	0	30,000	0
2	1.800	20.0	1.360 ⊥⊥ 0.529 ⊥	0	30,000	0
3	1.800	40.0	1.360 ⊥⊥ 0.529 ⊥	0	30,000	0
4	1.800	0	1.360 ⊥⊥ 0.529 ⊥	20.0	30,000	0
5	1.800	0	1.360 ⊥⊥ 0.529 ⊥	0	30,000	60.0
6	1.800	20.0	1.360 ⊥⊥ 0.529 ⊥	10.0	30,000	40.0

⊥⊥ = Parallel E Value for Flexure
⊥ = Perpendicular E Value for Flexure
COV = Coefficient of Variation
*Based on gross untransformed section.

→ 8d nails spaced at 8-in. intervals along joists

Note: Joist MOE and slip modulus vales are assigned independently.

E of tongue and groove joint elements = 10,000 psi for joints in both directions and for both axial load and bending (tightly butted tongue and groove joints)
All joint elements 0.10 in. long (for all 24 simulations).

More information on the correlation of slip modulus and material E over the range required in this report has not been reported in the literature. Establishing such a relationship is outside the scope of this report.

A uniform normal loading of 40 pounds per square foot (psf) was used in all of the simulations reported in this chapter.

The number of floors needed in each simulation to obtain the desired five percent error of the estimate for the mean maximum deflection was established prior to running these simulations. The error estimation procedure outlined by Dawson (4, 5) was used along with the highest response variation and adjusted student's population parameters reported by him to obtain this estimate. Thirty-one floors per simulation were required to obtain a desired five percent maximum error of the estimate value. However twenty-five floors per simulation were used to reduce computer costs and to give an even four percent frequency of plotting ease. Only one simulation was expected to exceed the five percent error of the estimate value and then by slightly more than one-half of a percent.

3.2 Material Simulations

The floor simulations were conducted in the order shown in Table 3.1. Only the floor joist E values were varied in the first three simulations. Joist E was randomly and separately selected for each joist from a Weibull distribution for each of the twenty-five floors included in the simulations generated for each chosen degree of material variability. Cumulative maximum joist deflection, joist tension stress and nail shearing force distributions for the floors in these three simulations are shown in Figs. 3.2, 3.3 and 3.4 respectively. In these

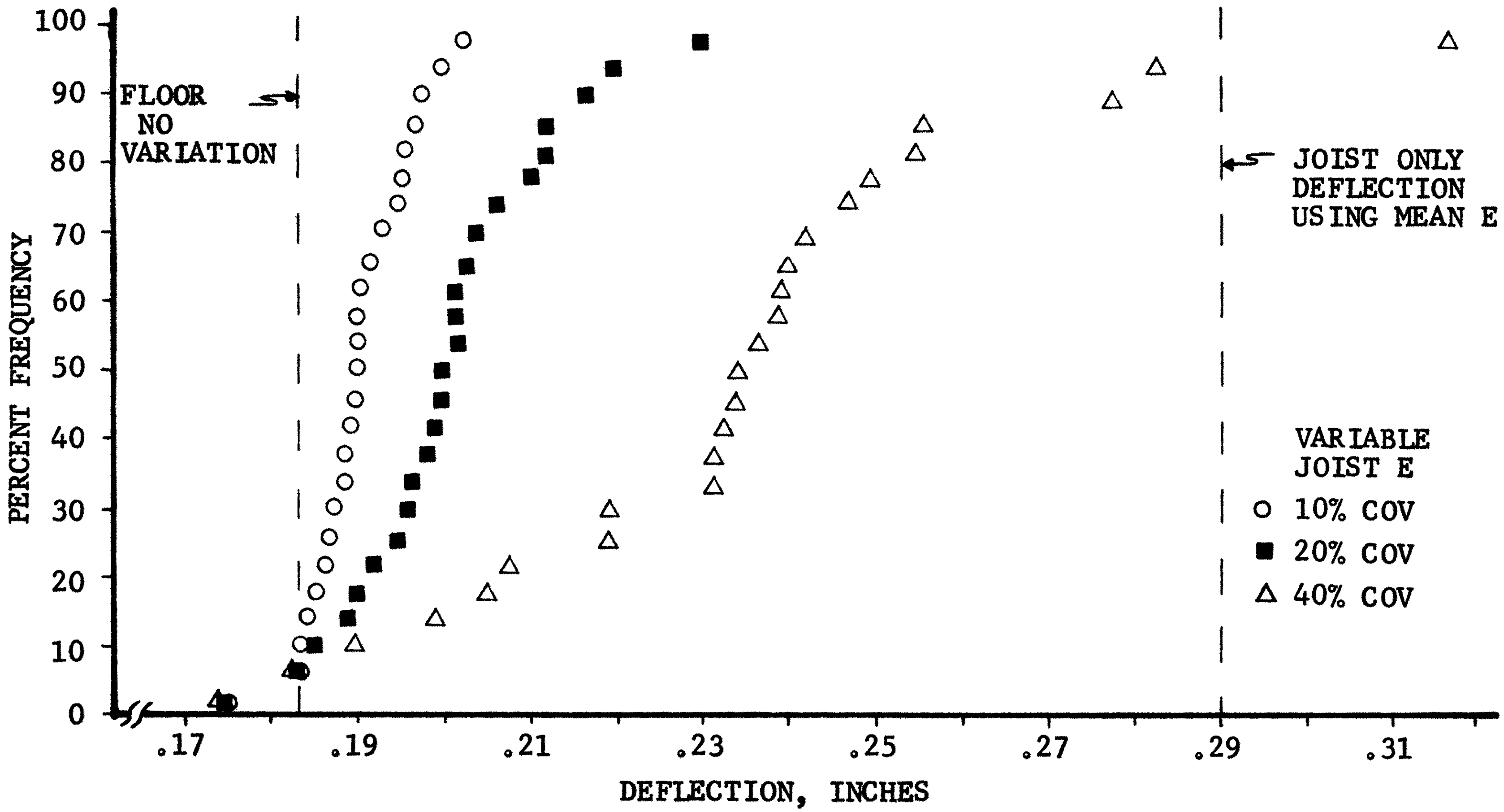


FIGURE 3.2

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATIONS 1,2 AND 3

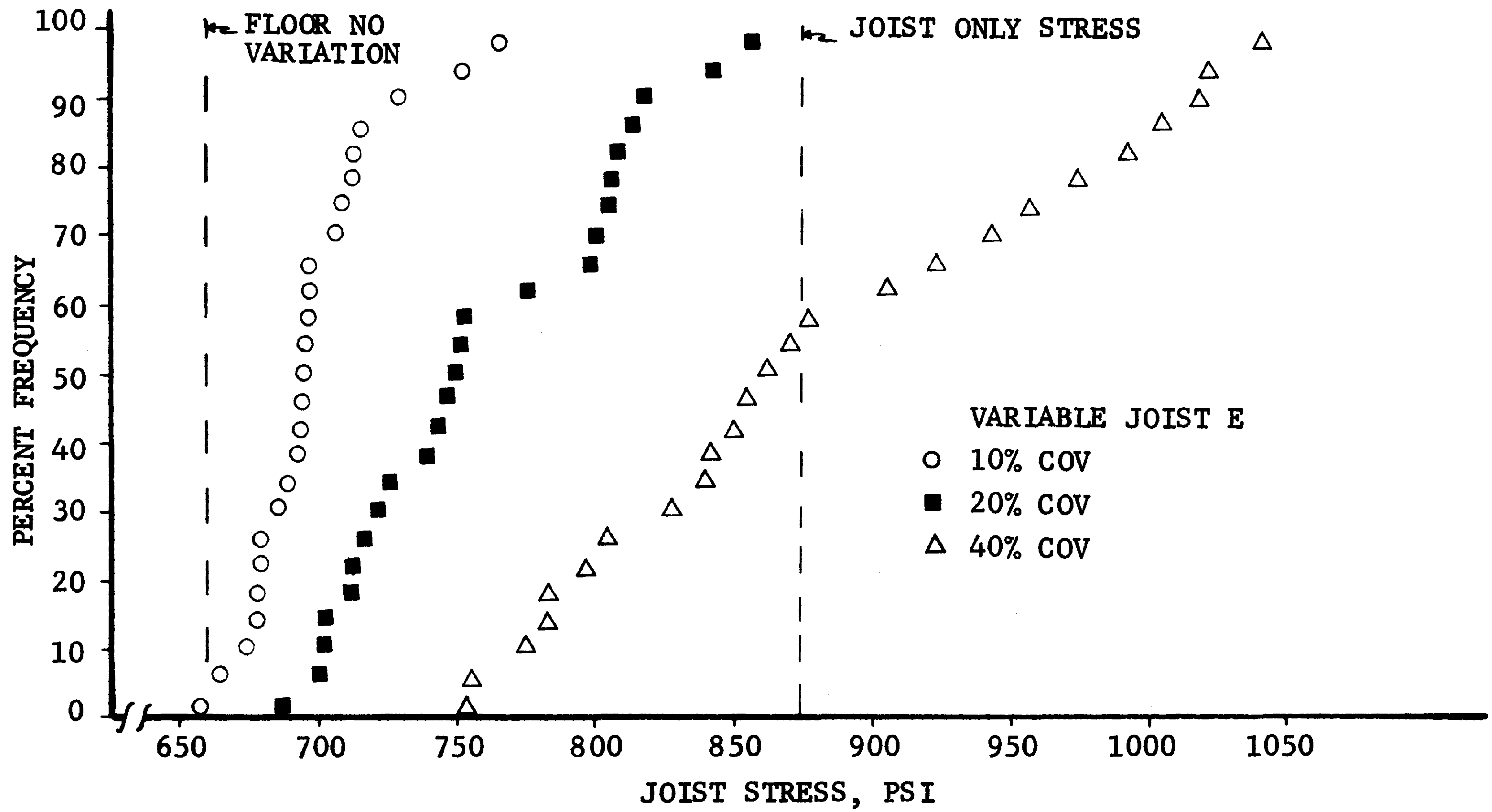


FIGURE 3.3
CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATIONS 1,2 AND 3

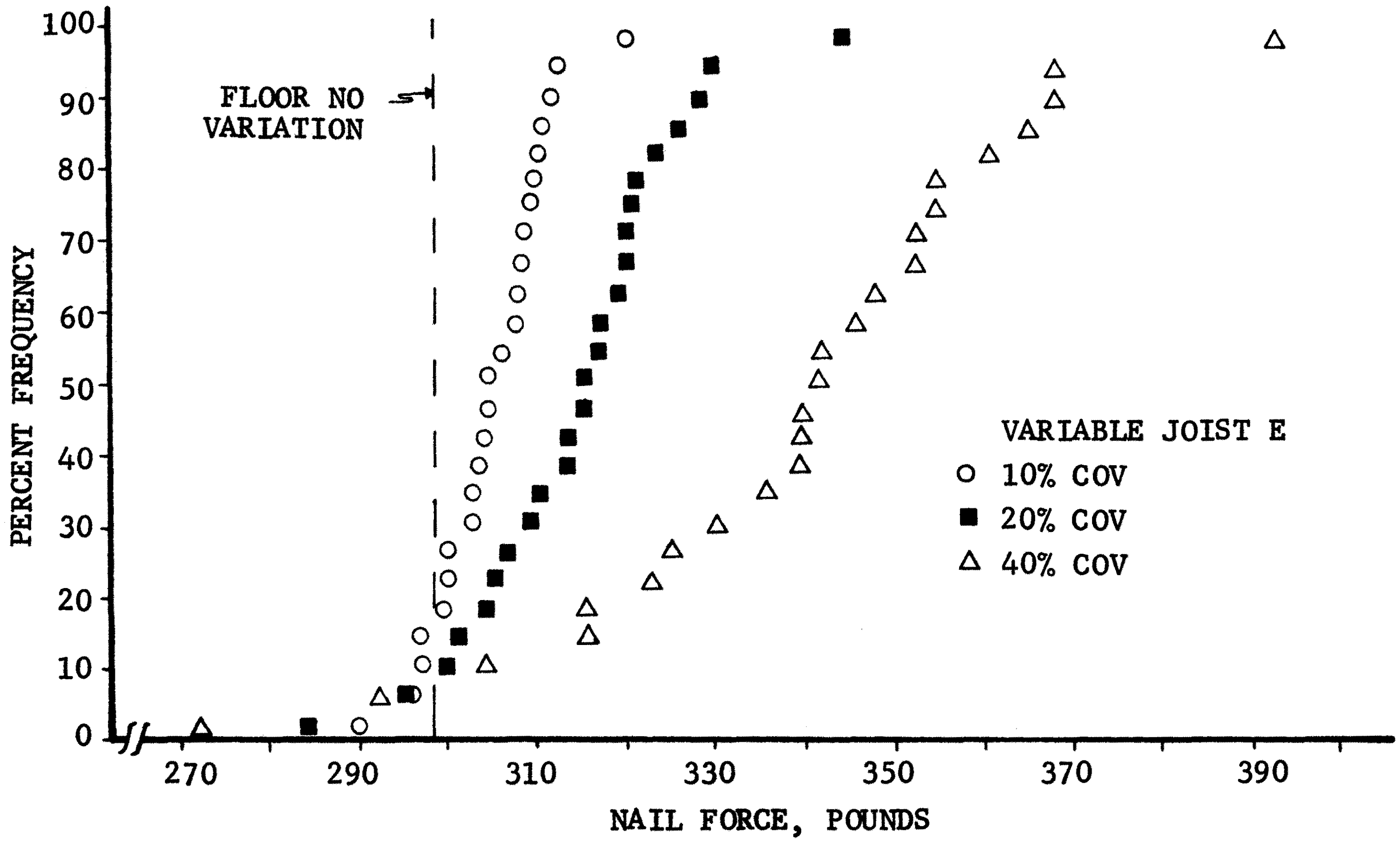


FIGURE 3.4

CUMULATIVE MAXIMUM NAIL FORCE DISTRIBUTION - SIMULATIONS 1,2 AND 3 plots the vertical axis denotes the percentage of floors having a response value (deflection, joist stress or nail force) below or equal to the value shown on the corresponding point on the horizontal axis. In these plots the dashed line labeled as floor no variation is the maximum response with all material properties having the mean value. The dashed line labeled as joist-only deflection or joist stress is the corresponding response of a joist with the mean MOE value loaded by the load over its tributary area. The cumulative distribution or frequency plots show that the response variation increases as the joist E variation increases. This increase is quite pronounced for the floors displaying the larger response value (i.e., those with higher frequencies). The deflection distributions show that for high joist E variations it is possible for maximum deflections to be greater than a joist-only calculated deflection computed with a mean E. Maximum deflections most often occur as a result of several joists with a low E being grouped in the floor system. However, a large majority of the maximum deflections are well below that of the joist only calculated deflection. These results compare well with those previously reported by Dawson (4, 5).

The joist stress distribution in Fig. 3.3 shows that the joist only stress, calculated using the elementary flexural formula, is often surpassed by the maximum joist stress in a given floor. It should be noted, however, that even the 1042 psi joist stress value computed for the most highly stressed of the 825 joists contained in the floors of these three simulations is not an excessively large stress. For No. 1 Douglas-fir larch joists the NDS (1) permits an allowable stress of 1500 psi for bending stress for single use members (1750 psi for repetitive member use) and 1000 psi tensile stress. With the plywood acting as a compression flange the joist is loaded with both an axial tension and a bending force. The proper allowable stress is at some yet undefined value within the 1000 to 1500 psi interval.

Nail forces can also become large, approaching 400 pounds per nail, as is shown in Fig. 3.4. This value is significantly larger than the 64 to 78 pounds per nail that is allowed in the NDS (1).

In all cumulative distribution plots, a dashed line indicating the response resulting with no variability in the system is shown. Figures 3.2, 3.3 and 3.4 show that it is possible to achieve maximum response values less than that with the no variation condition. This behavior can occur when the average joist stiffness resulting from the random selection is sufficiently high. Maximum joist stresses did not fall below the no variability case because the sum of all the joist stresses in the floor are fairly well set by the conditions of statics (equilibrium). Any variation in the floor would result in some joist carrying proportionately more load and thus it would have a higher stress than the average value for the floor.

An alternate method of showing the reduction in deflection which occurs when treating the floor system as an integrated unit, as opposed to a series of isolated joists without assistance from the sheathing, is shown in Fig. 3.5. In this comparison, the simulated floor response with joist stiffness variability is compared not with the no-variation joist-only values but with the variability also existing for the joist-only model. The maximum deflection in each floor is shown to be much less than the maximum deflection given by the joist-only calculation. For the joist-only calculation, the maximum deflection is the

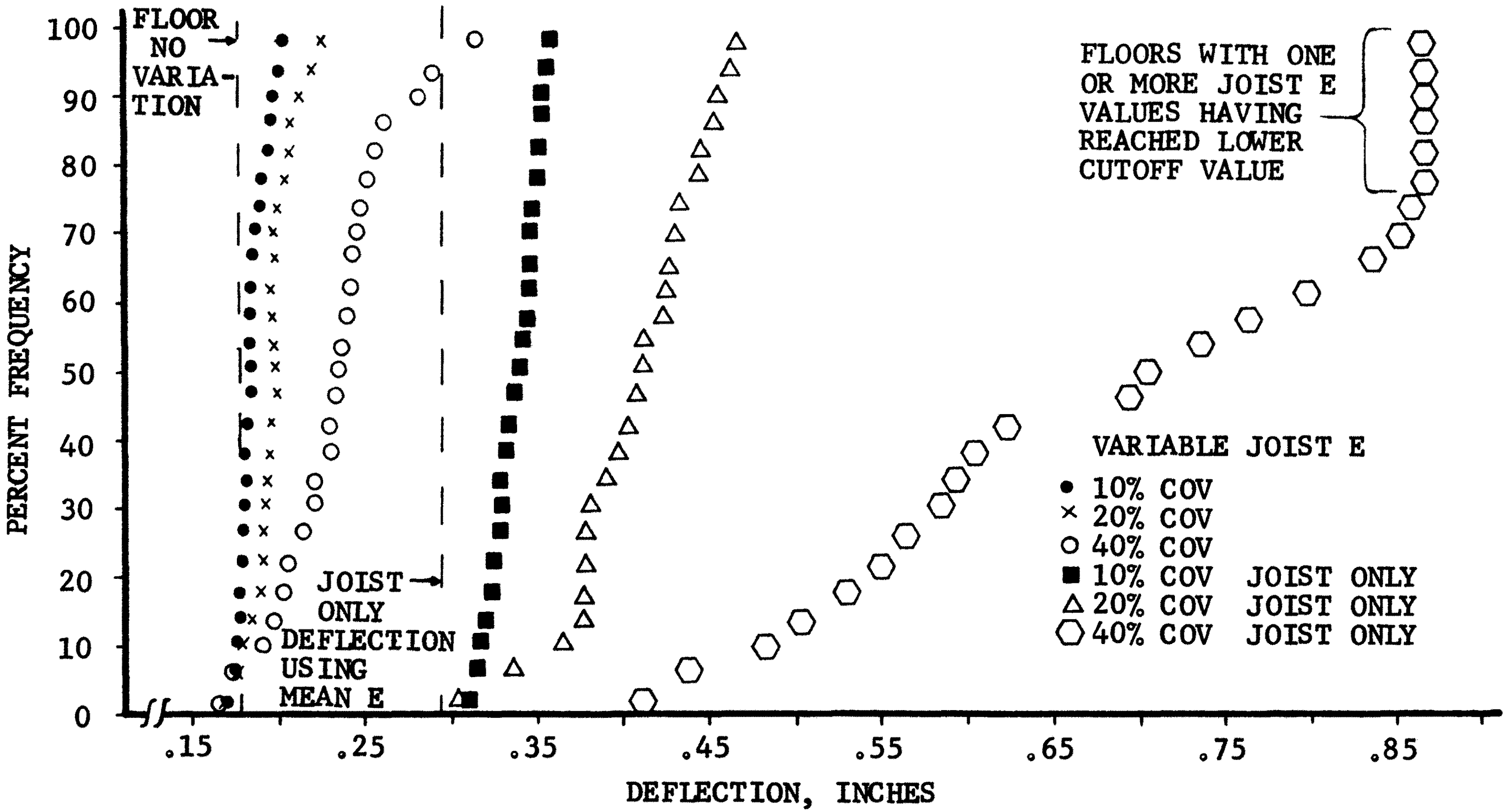


FIGURE 3.5

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATIONS 1,2 AND 3

$5wL^4/384EI$ value for each joist having the lowest E value, where w is the load over the tributary area of the joist expressed as a uniform line load.

Plywood E was also varied alone in a separate simulation labeled as simulation number 4 in Table 3.1. Plywood E in the direction parallel to the face ply grain was randomly selected from a Weibull distribution. A corresponding perpendicular E value was computed using a constant factor computed as the ratio of mean parallel E value to mean perpendicular E value. A material coefficient of variation value of 20 percent was selected for this simulation with plywood E only varied. This value was chosen to represent a fairly large level of variability in the plywood material. The laminated characteristic of plywood should result in plywood variability being less than that of joists. Because of the fairly low effect plywood variability had on floor response variability, the additional information which would be obtained from more simulations with lower plywood E variabilities was deemed to be too small to justify conducting these additional simulations (see Fig. 3.6).

Cumulative maximum deflection and joist stress distributions for each of the twenty-five floors for Simulation 4 with variable plywood E are shown in Figures 3.6 and 3.7 respectively. The horizontal scales in each of these plots have been greatly expanded. The nail force distribution has not been shown primarily because the maximum values change only slightly between floors. A comparison of the ranges of maximum deflections and joist stresses resulting from the 20 percent plywood E coefficient of variation with those resulting with variable joist E shows that joist E variability is the much more important

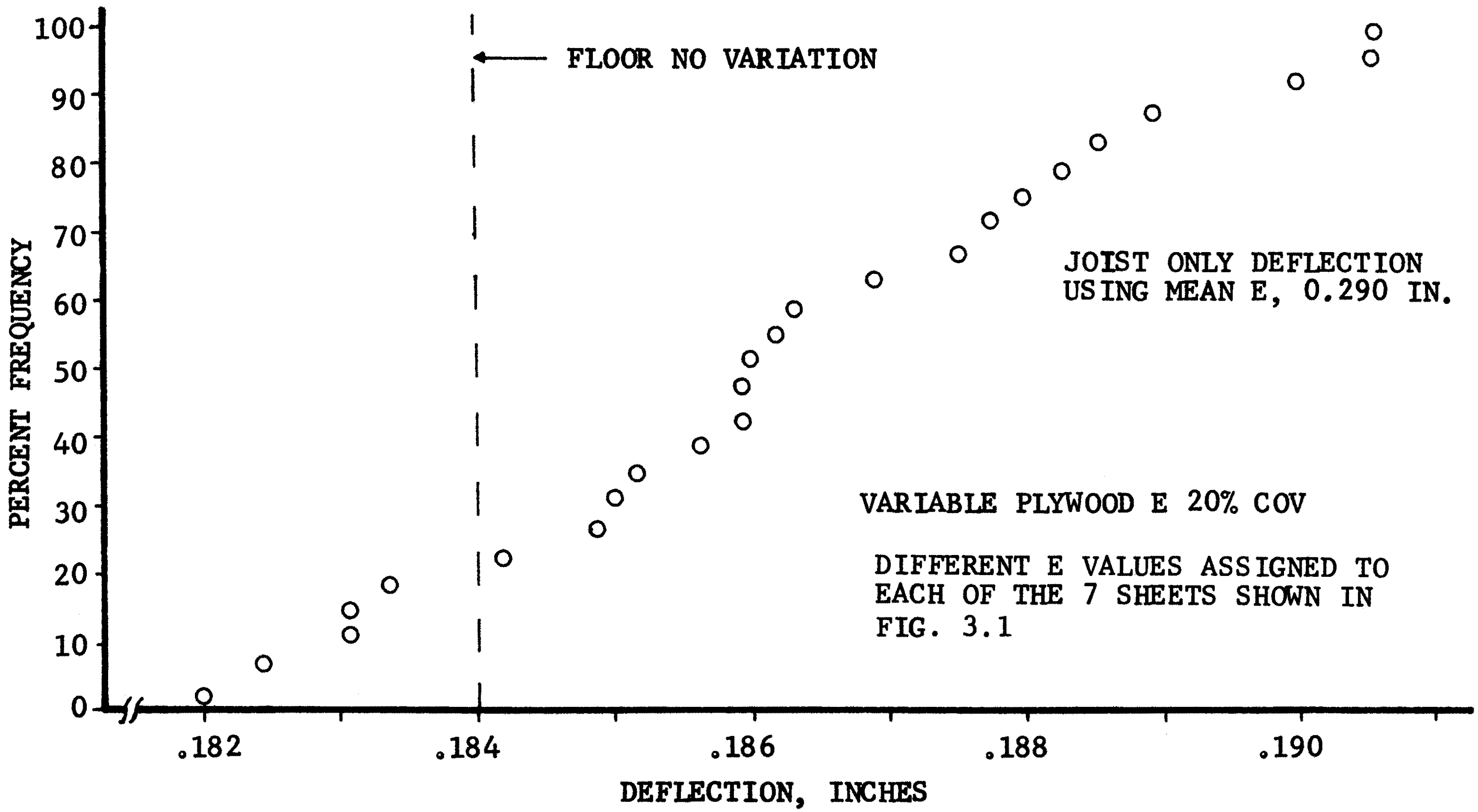


FIGURE 3.6

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 4

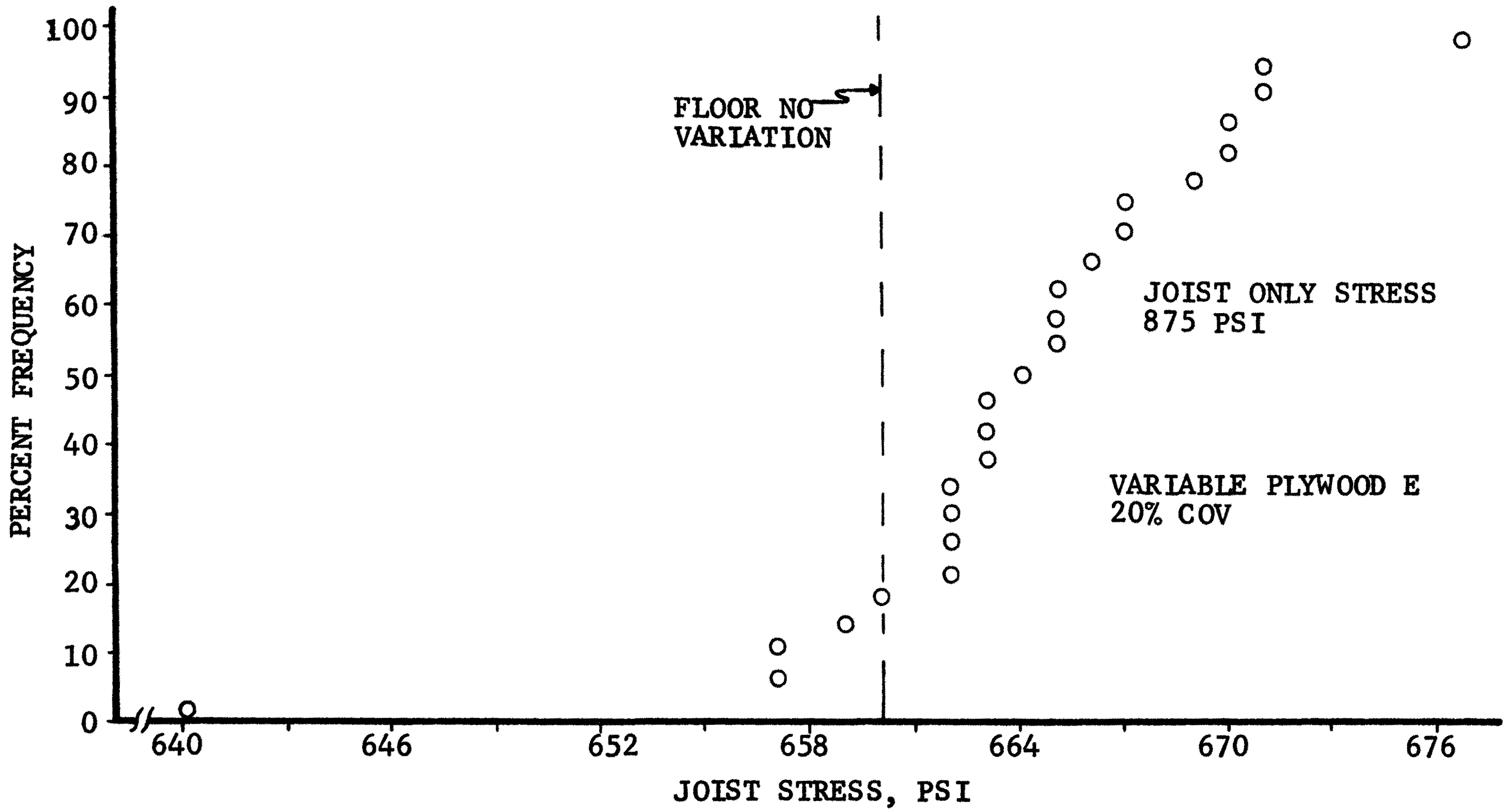


FIGURE 3.7

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION-- SIMULATION 4 parameter. Indeed, the response variability is only slightly affected by the plywood E variation, even for these floors with a plywood thickness larger than would be expected in the average floor.

Slip modulus was next varied alone. The value assigned at random for each joist was held constant along the joist length. A larger than average variation (COV value for slip modulus = 60 percent) was chosen (see Simulation 5 in Table 3.1). Cumulative maximum joist deflection and joist tensile stress distributions are shown in Figs. 3.8 and 3.9 respectively. The response range, plotted on an expended scale, is small considering a slip modulus COV of 60 percent was used. Based primarily on these results, no additional simulations using smaller coefficient of variation values were conducted for slip modulus variation only.

The responses of the floors included in these first five simulations are presented in another form in Appendix A. Data for the twenty-five floors within each group have been arranged in an order determined by the average deflection or stress of the middle nine joists of each floor. The level of variation of joist deflections or stresses within each floor is indicated by the interval extending one standard deviation of these joist responses above and below the mean value. Also shown is the maximum joist deflection or stress for each floor. It is these last values that have been plotted on Figs. 3.2, 3.3, 3.6, 3.7, 3.8 and 3.9. Although the maximum joist deflections and stresses tend to occur for floors with high average responses, the sequence of floors do change some when ordered on the basis of mean response. An examination of the plots in Appendix A shows that the average joist response, even in the floors which had high maximum joist

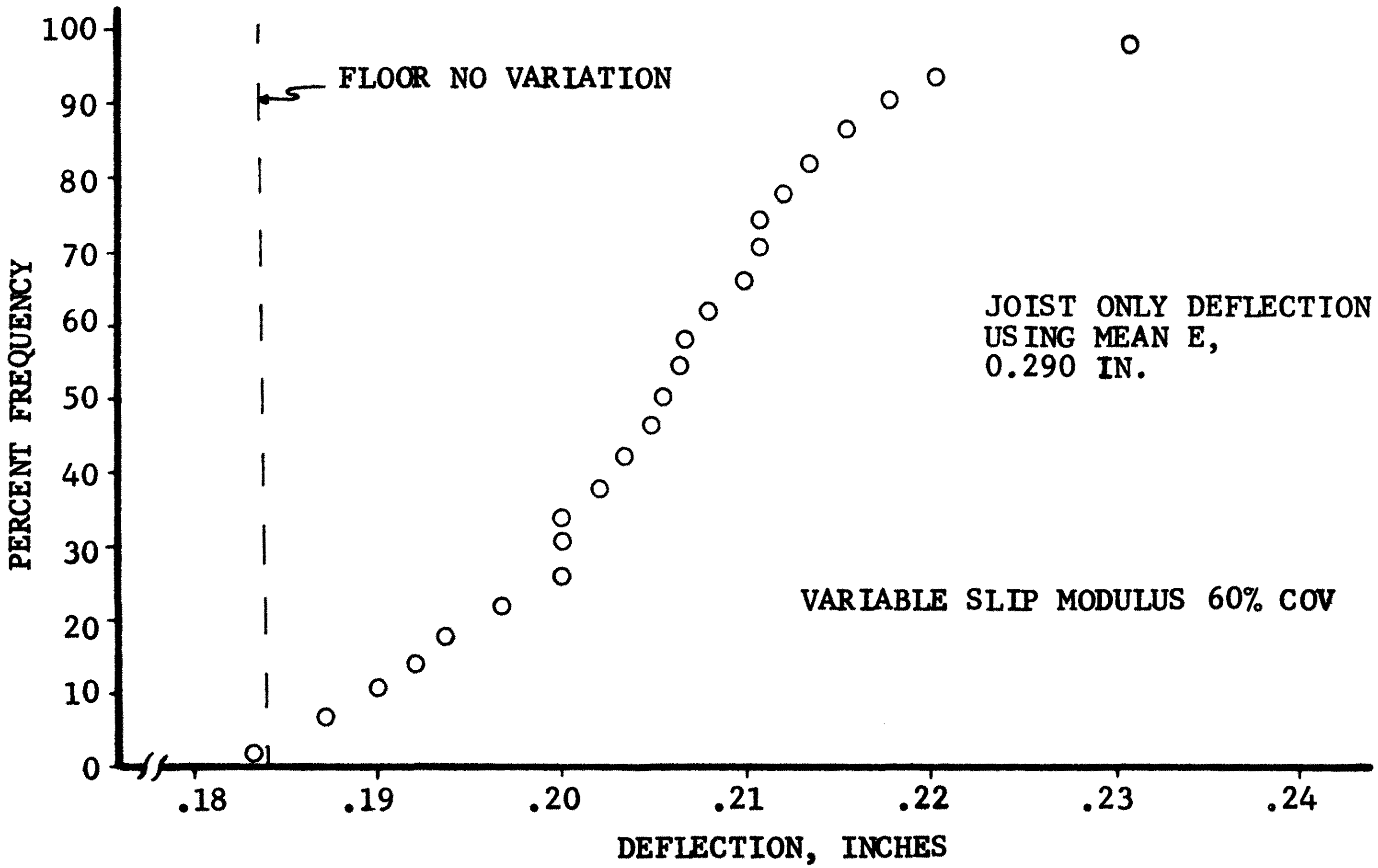


FIGURE 3.8

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 5

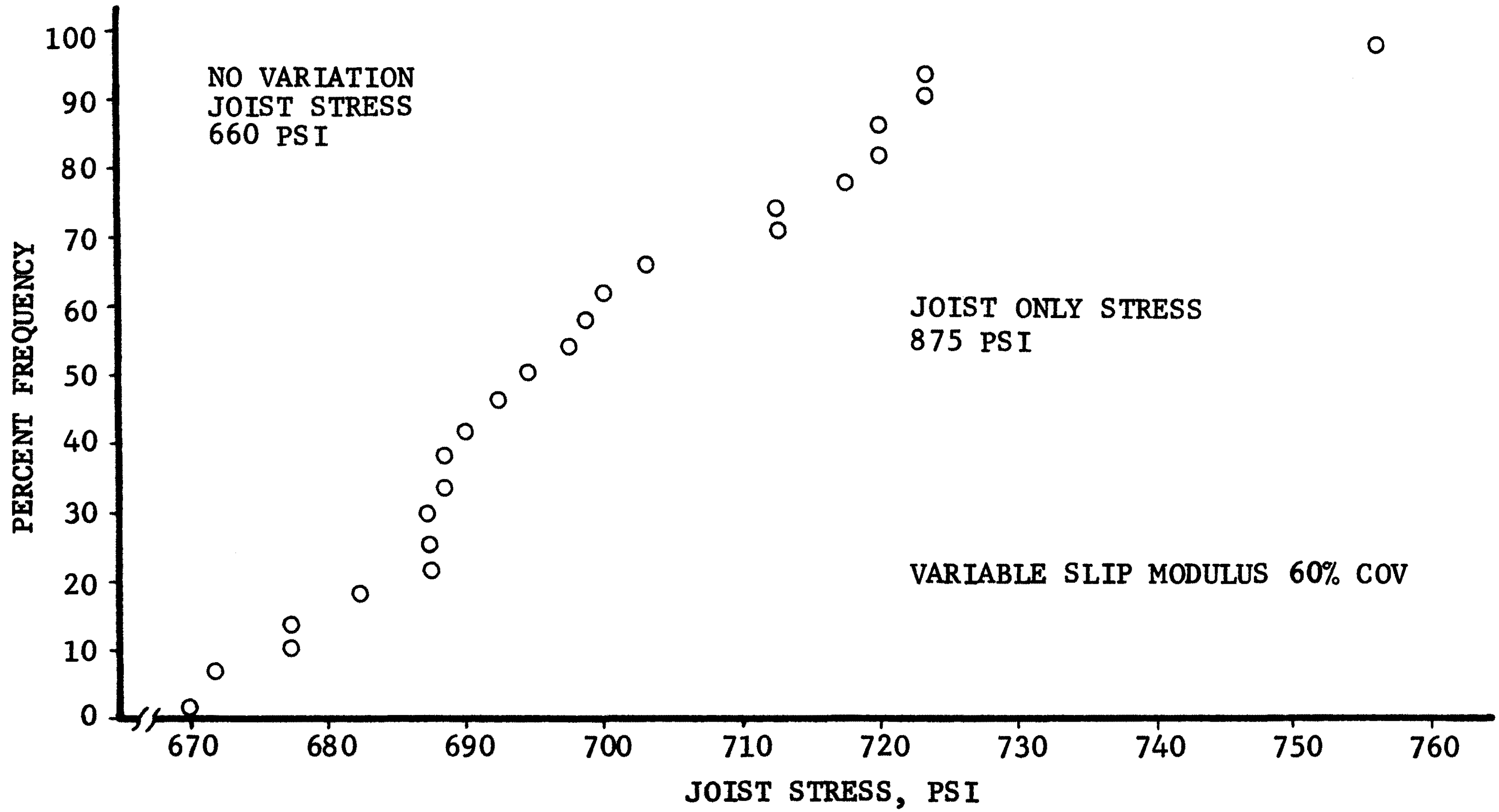


FIGURE 3.9
CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 5

deflection and stress values, are much nearer the value predicted for the floor system without variation than that given by the joist-only model. The average joist deflection values vary around the no-variability value, as would be expected.

A sixth simulation was performed to approximate actual floor response. These floors had the material properties given in Table 3.1. Levels of variability assumed were 20 percent, 10 percent and 40 percent for the joist E, plywood E and slip modulus, respectively. Cumulative maximum deflection, joist stress and nail force distributions are shown in Figs. 3.10, 3.11 and 3.12 along with the results for the same basic floor with only joist E varied with the same COV used for the floors of Simulation 6. Maximum deflections and joist stresses of Simulation 6 increase only slightly from those of Simulation 2 (joist E only variable). This is added evidence that varying only plywood E and slip modulus has a slight effect on the response variation of floors. However, Fig. 3.12 shows a considerable difference in the maximum nail force distributions between floors 2 and 6. Therefore, varying the slip modulus or plywood E or both has a considerable effect on the maximum nail force variation in the direction of the T-beams. The variation in nail force is expected to be at least partly affected some by the slip modulus because the nail force is directly related to the connector stiffness. The stiffer connector transfers more force than the more flexible connector in order to satisfy compatability conditions. These figures provide a qualitative measure of how much variation of response should be expected among the separate floor. In addition to the information on the response variation contained within each floor given in Appendix A,

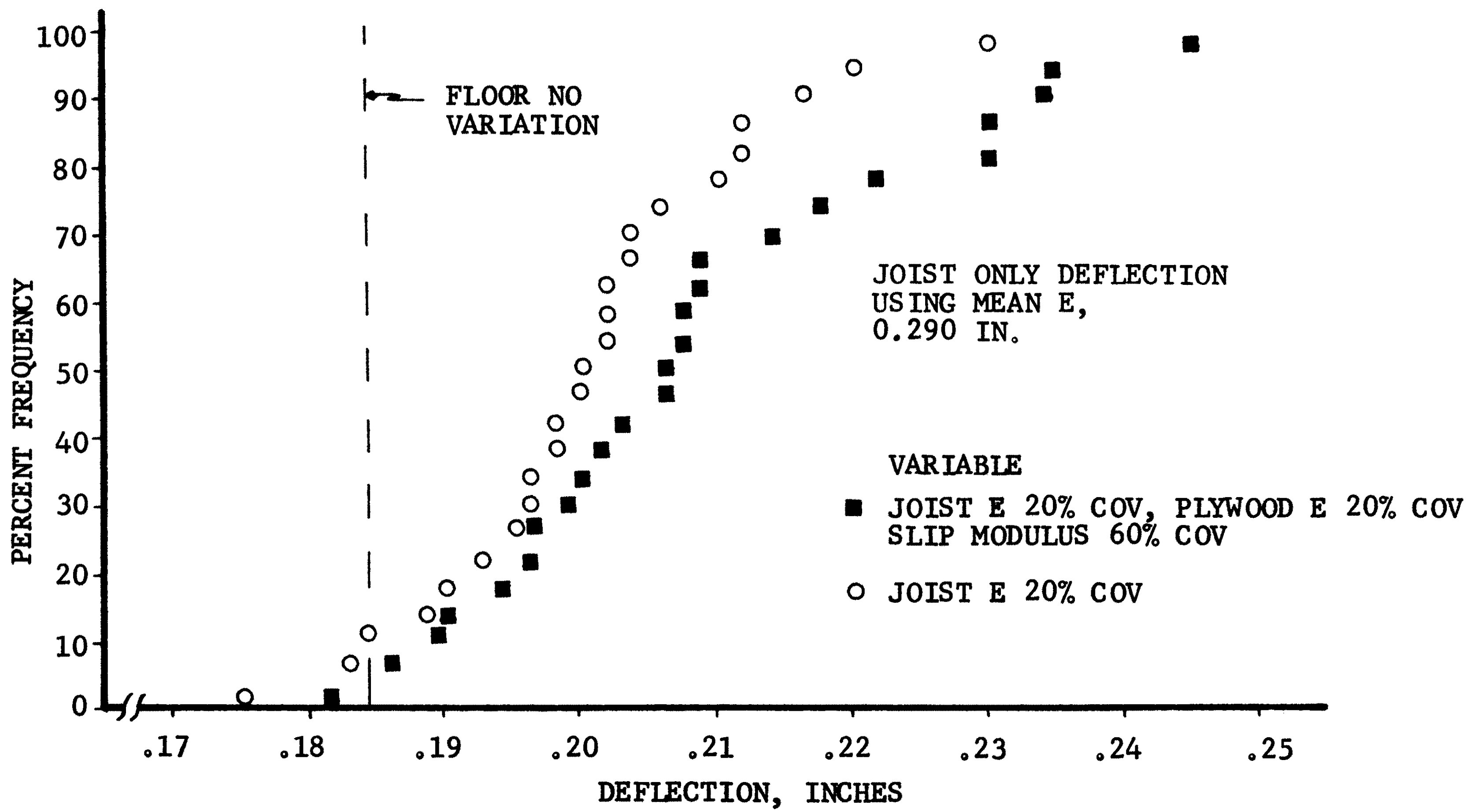


FIGURE 3.10

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATIONS 2 AND 6

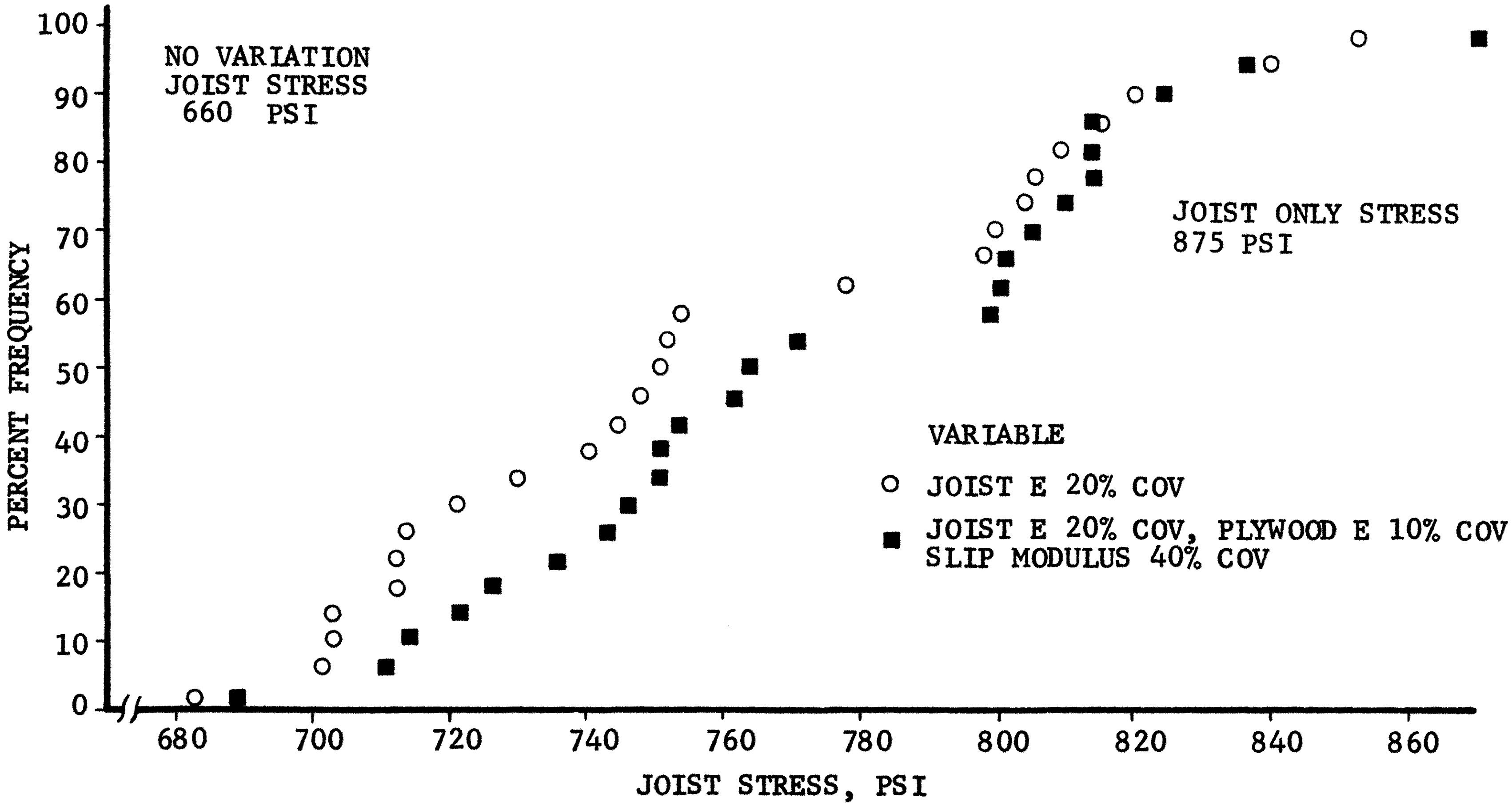


FIGURE 3.11

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATIONS 2 AND 6

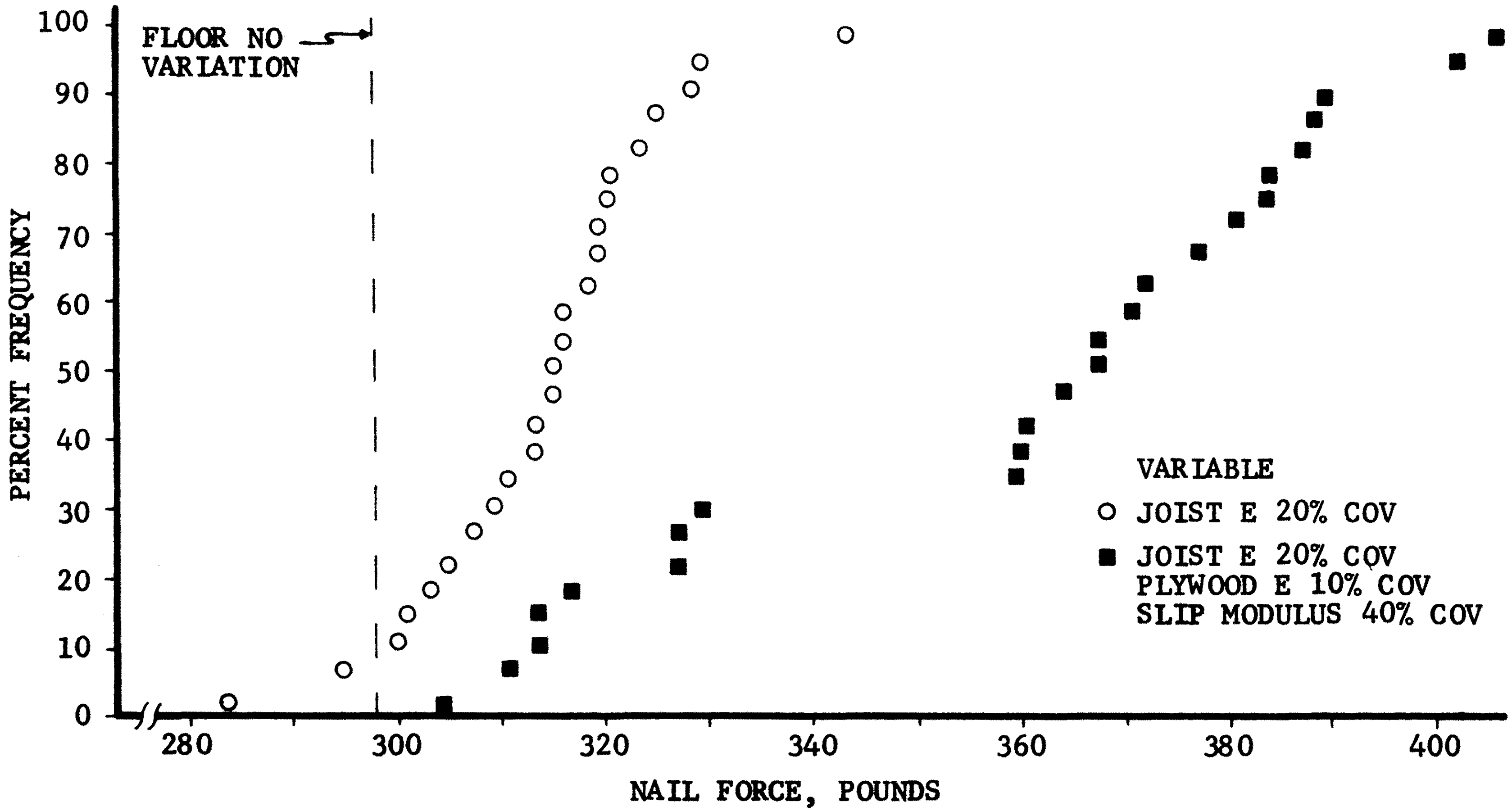


FIGURE 3.12

CUMULATIVE MAXIMUM NAIL FORCE DISTRIBUTION - SIMULATIONS 2 AND 6 the deflection and joist stress response of a typical floor from each of these first six simulation studies of the basic floor system are shown in Appendix E.

3.3 Comparison of Material and Response Variability

The first objective of this study is to define the effect of material variability on wood joist floor response. The influence of component property variability on the floor response variability can be summarized by a relationship giving the mean and variability of the response as a function of these properties of the input values. In this section, such a relationship for response variability and mean maximum value will be constructed for each material stiffness variability using the results from the first five simulations. This relationship, when established, allows both a convenient way to quantify the effect of material variations and a way to predict the response characteristics when levels of COV values other than those investigated are of interest. These curves should also give reasonable estimates of the response variation characteristics of floors having slightly different component size and mean strength combinations.

Dawson (4, 5) reported that deflection variability increases in an approximately linear manner with an increase of the joist variability. This previously reported observation and the results of Section 3.2 support the hypothesis that an approximately linear relationship exists between component COV and response coefficient of variation. Using the assumption of a linear relationship and the simulation results, Figs. 3.13, 3.14 and 3.15 have been constructed to show the variation of deflection, joist stress and nail forces in terms of the variability of one structural component material property. The

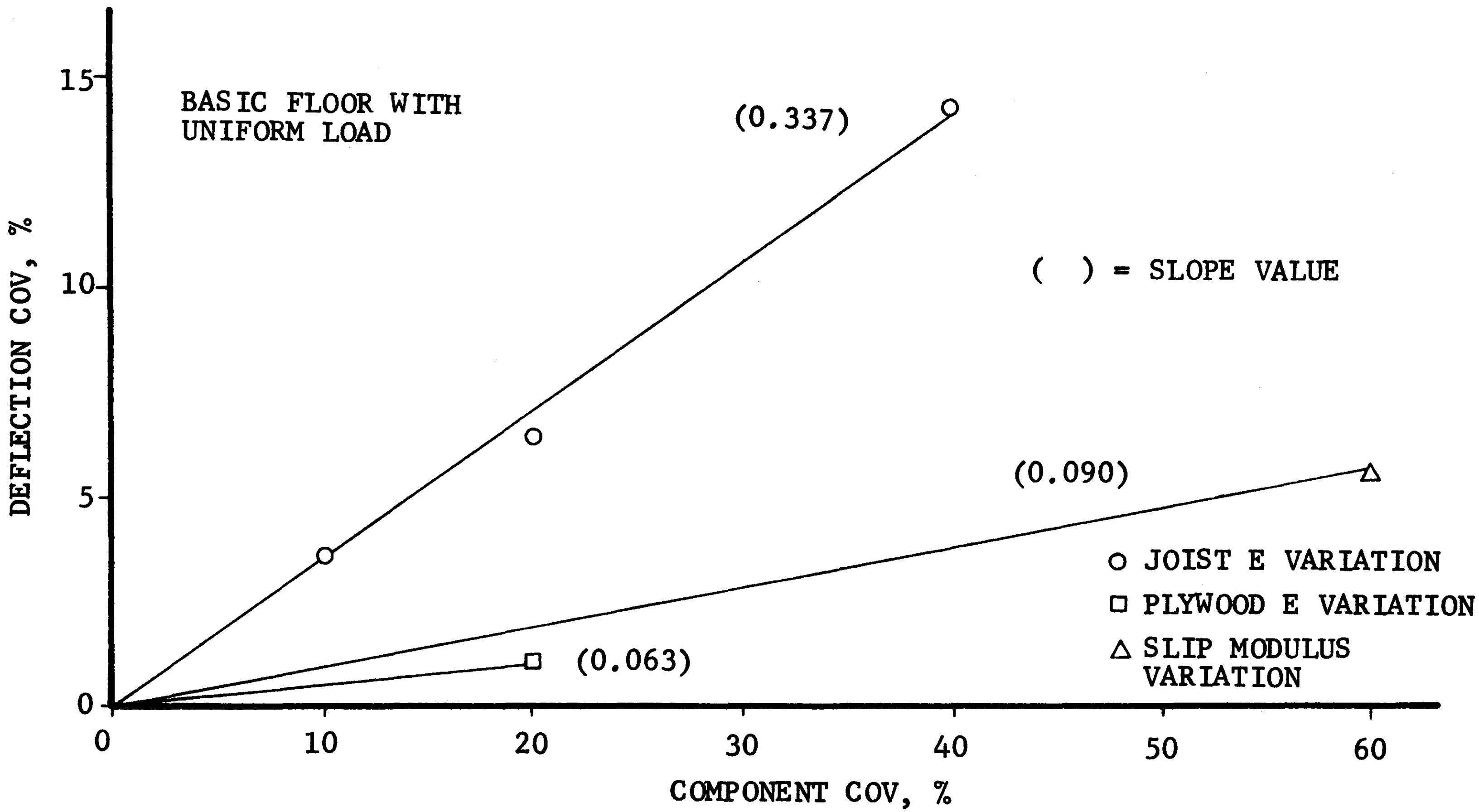


FIGURE 3.13
COMPONENT COV V.S. MAXIMUM DEFLECTION COV - SIMULATIONS 1,2,3,4 AND 5

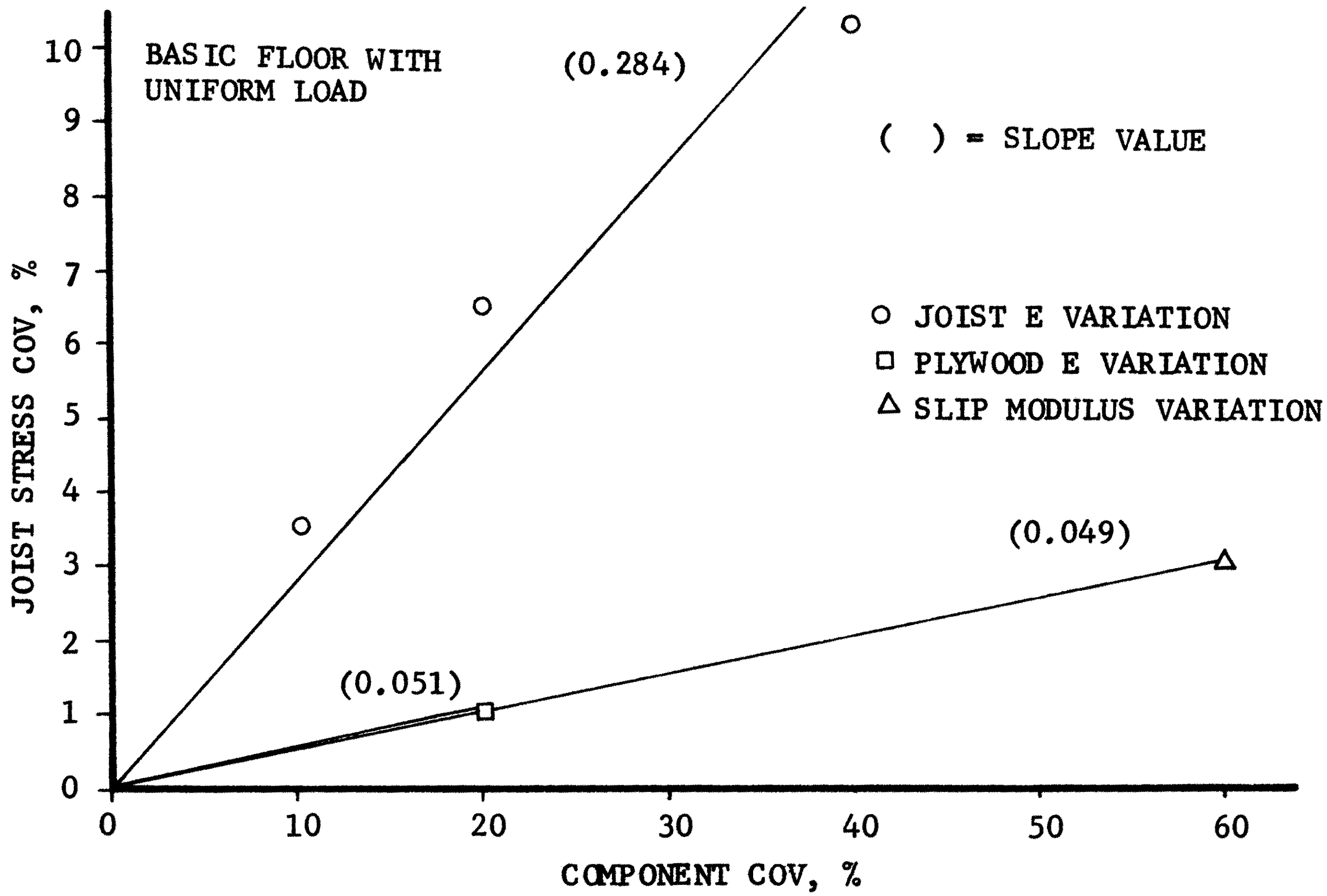


FIGURE 3.14

COMPONENT COV V.S. MAXIMUM JOIST STRESS COV - SIMULATIONS 1,2,3,4 AND 5

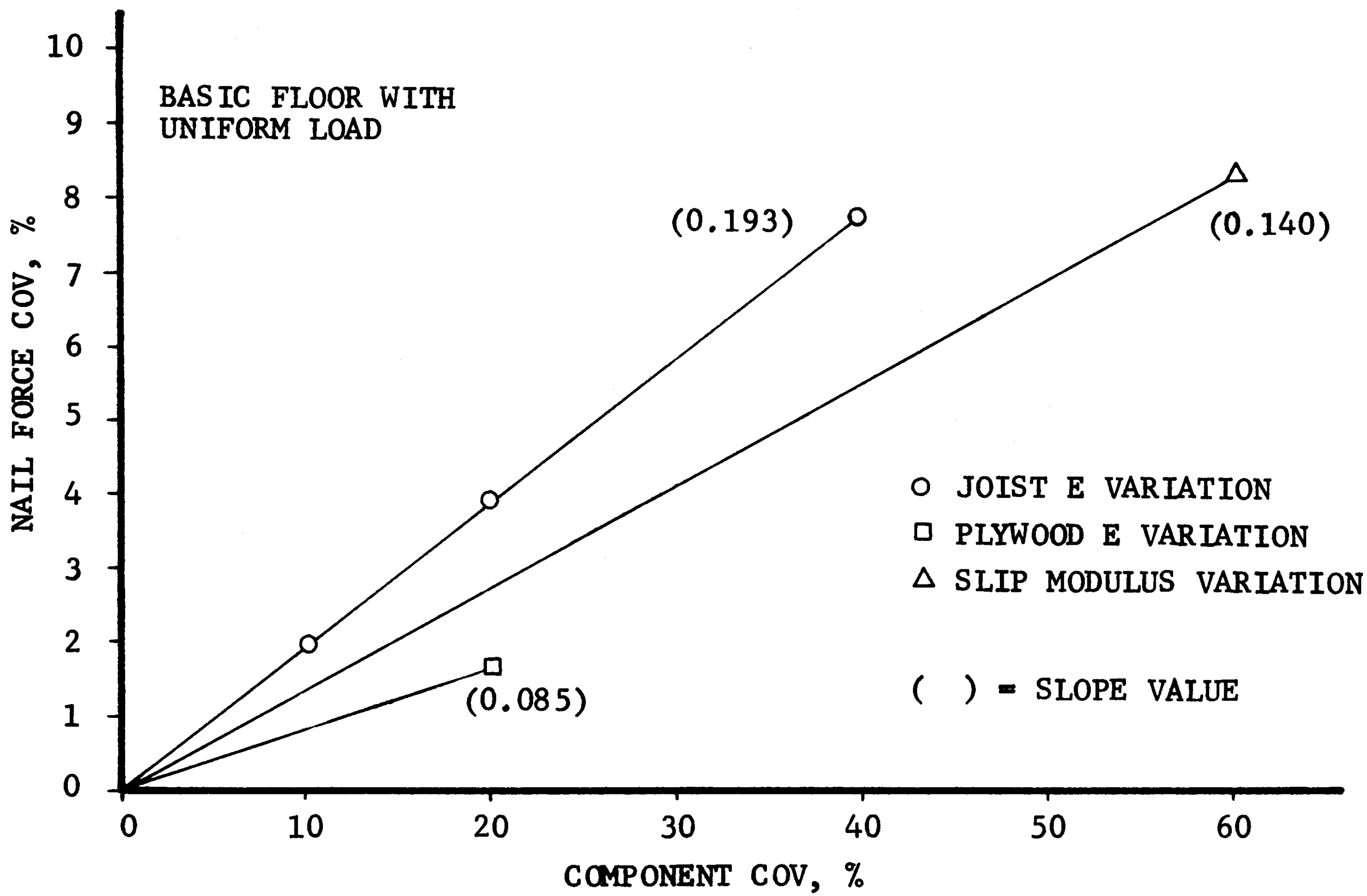


FIGURE 3.15

COMPONENT COV V.S. MAXIMUM NAIL FORCE COV - SIMULATIONS 1,2,3,4 AND 5 variation in the maximum joist deflection due to joist E variation is seen to be over three times greater than that resulting from either slip modulus or plywood E variation (Fig. 3.13). The component interaction is successful in considerably reducing the influence of even the joist stiffness variability. The maximum joist deflection variability, as measured by its coefficient of variation, is 34 percent of the individual joist variability. Floor deflection variability was only 9.0 and 6.3 percent of the slip modulus variability and plywood stiffness variability, respectively. The influence of material variability on maximum joist stress variation is shown in Fig. 3.14. The joist stress response is most affected by the joist E variation. Its effect is about five times that of either the plywood E or slip modulus variation. Variability of any of the three components (joist E, plywood E and slip modulus) affects the nail force variation by much more nearly the same amount, although joist E variability is still more influential.

Using the slopes of the relationships given on Figs. 3.13, 3.14 and 3.15, a predictor equation assuming this linear relationship can be developed to determine the maximum response COV (percent) as the given slope multiplied by the material stiffness COV (percent). For example, the maximum deflection COV expected to result from a joist E variability of 30 percent is equal to 0.337 times 30 or 10.11 percent. Obviously these relationships are only valid for the mean value material properties given in Table 3.1, the floor configuration shown in Fig. 3.1, and the uniform loading condition.

The relationships observed between material property component COV and the mean maximum floor response are presented in Figs. 3.16, 3.17 and 3.18. Based upon the same arguments as before, a linear relationship was assumed for change in the mean of the maximum joist E COV that fits the slightly nonlinear trend shown by the data points in Fig. 3.16. Dawson's (4, 5) results agree with Fig. 3.16 and therefore the linear relationship is thought to be a reasonable approximation.

Variability of the joist E is the most significant of the three material properties in determining the mean maximum deflection and joist stress. These increases can be sizeable. Joists with a COV of 40 percent resulted in mean maximum deflection increasing 26 percent and mean joist tensile stress increasing 33 percent over the values of the floor without variable material properties. However, slip modulus variation is shown to be the most significant component in affecting the mean maximum nail force. A 28 percent increase in the mean maximum nail force is shown for a nail slip modulus COV of 60 percent. As would be expected, the mean maximum response of a component is heavily influenced by the variability of that same component. The slopes of the relationships for Figs. 3.16, 3.17 and 3.18 are given on these figures. Using these slopes, predictor equations can be written as follows assuming a linear relationship:

$$\Delta = \Delta_o \; (1 + M_i(COV_i)) \qquad (6)$$

where Δ is the mean maximum deflection in the variable floor system, Δ_o is the maximum deflection of the floor without variation, COV_i is the coefficient of variation of material component i in percent, and M_i is a constant applicable for material component i and computed as the slope of the relationships of Figs. 3.16, 3.17 and 3.18 divided by Δ_o. The magnitude of the quantity M_i thus expresses the

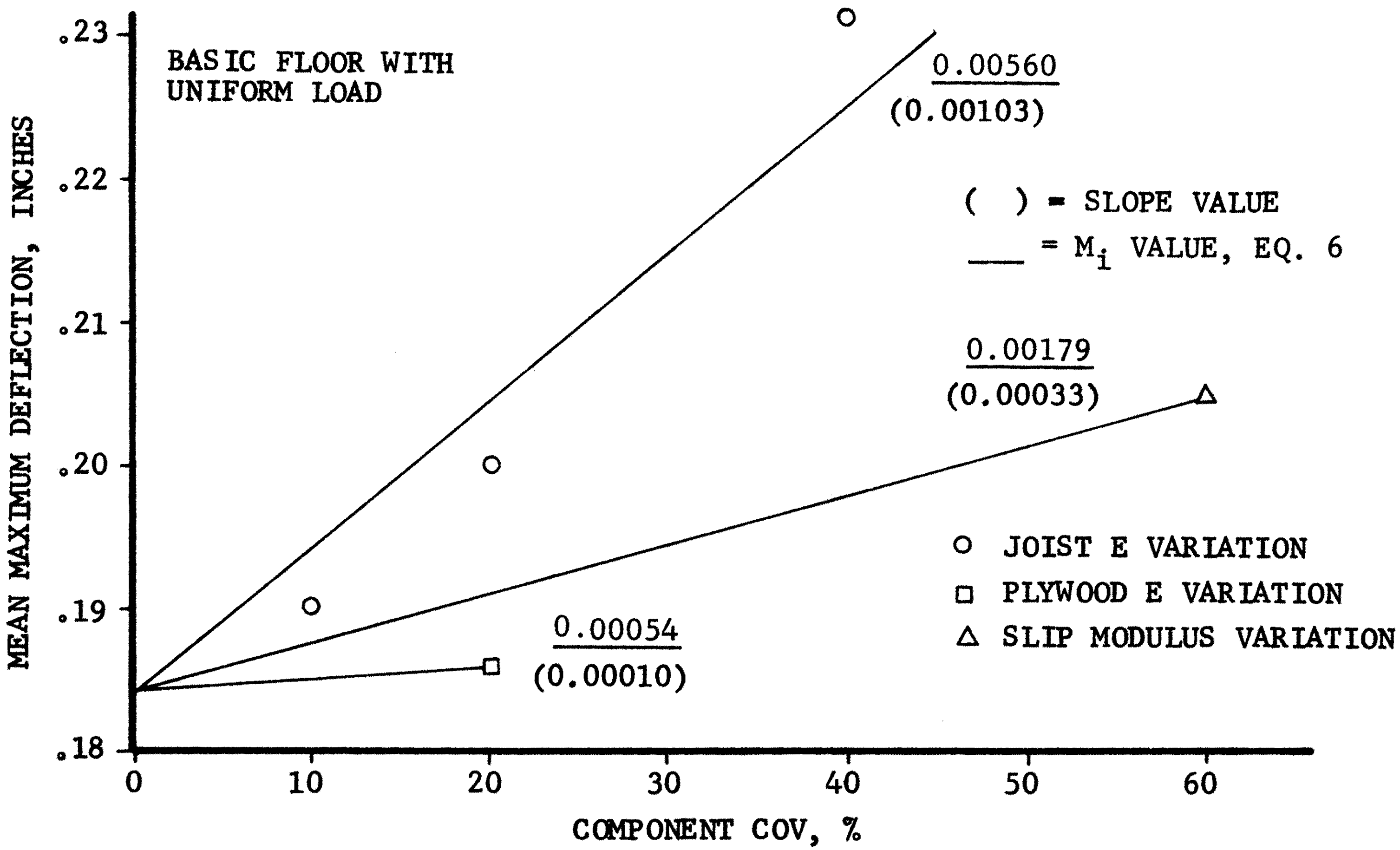


FIGURE 3.16

COMPONENT COV V.S. MEAN MAXIMUM DEFLECTION - SIMULATION 1,2,3,4 AND 5

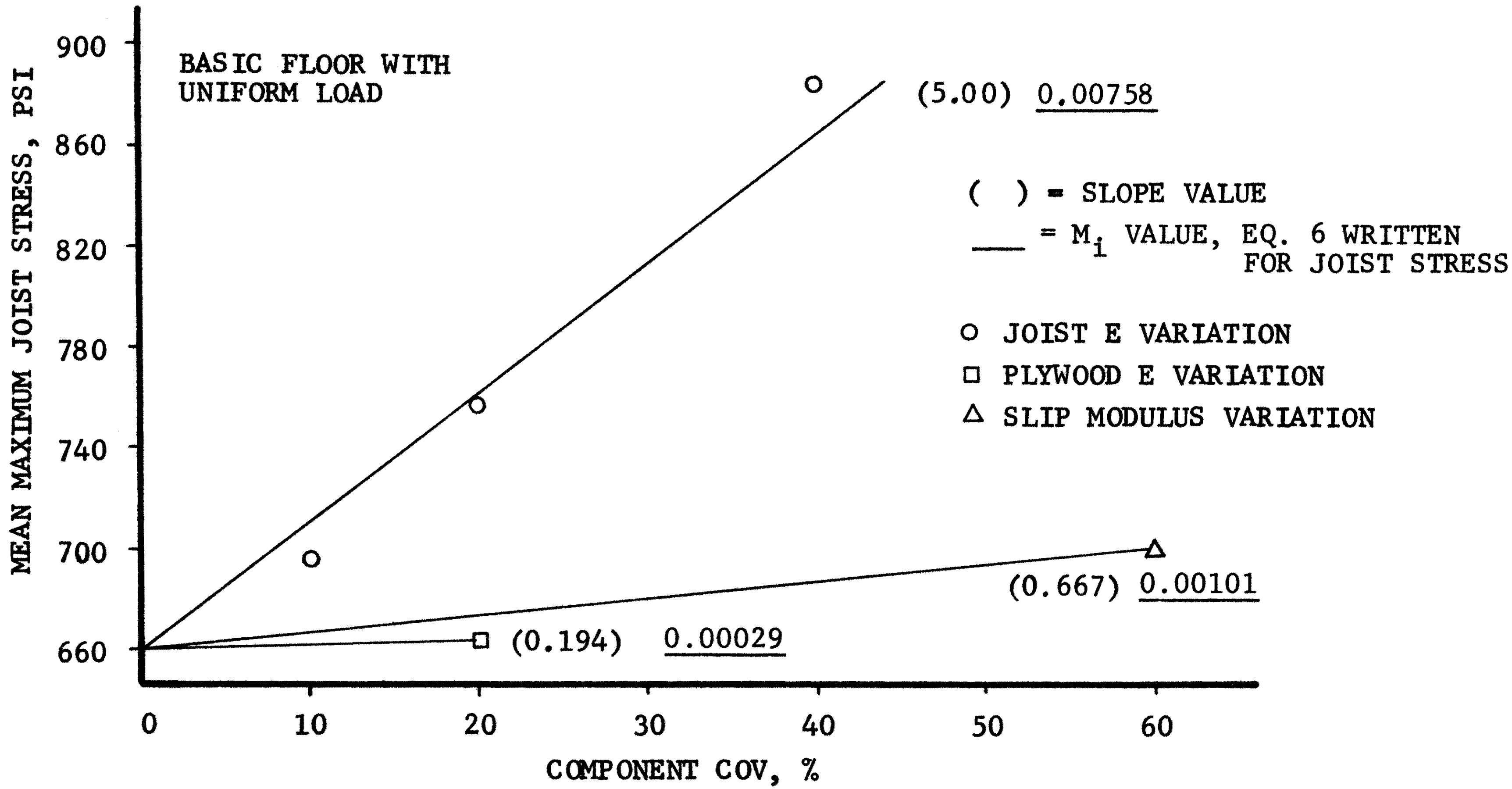


FIGURE 3.17

COMPONENT COV V.S. MEAN MAXIMUM JOIST STRESS - SIMULATIONS 1,2,3,4 AND 5

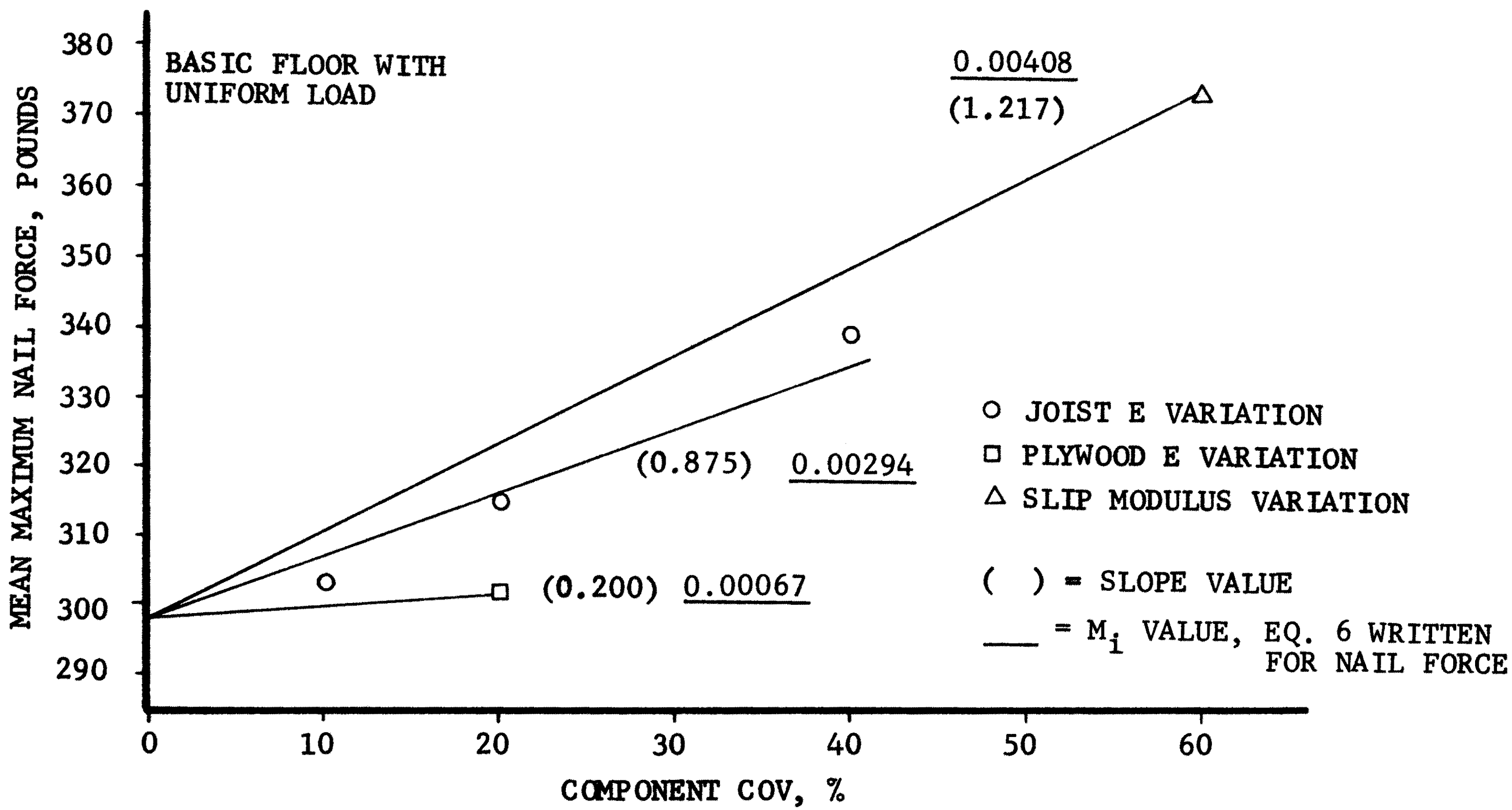


FIGURE 3.18

COMPONENT COV V.S. MEAN MAXIMUM NAIL FORCE - SIMULATIONS 1,2,3,4 AND 5 effect the material variability has on response variability. For example, an M_i value of 0.00560, the value found for the effect of joist stiffness variability, would indicate that a material stiffness COV value of 30 percent causes a 16.8 percent (0.00560*(30) = .1680) increase in the maximum response mean. The M_i values are listed on the appropriate plots and are later summarized in Table 6.2. Obviously the material components must have the same size and mean property value as given in Table 3.1 for these values to be valid.

The correlation between the maximum joist tensile stress and the stiffness of that joist is shown in Fig. 3.19. The more highly stressed joists are also generally those which have significantly higher than average stiffness. This is consistent with the explanation that the stiffer joist attracts more load. Also the spread of the twenty-five values from the floors for each COV considered increases as the joist E variation increases. The relationship between maximum joist stress within the floor and the stiffness of this joist is an approximately linear relationship.

Another way of examining the role of lateral load distribution is shown in Fig. 3.20. In this figure, joist stress is shown to be related to the ratio of the modulus of elasticity (E) of the joist (E_j) with the maximum stress to the average E of the adjacent joists ($1/2(E_{j-1} + E_{j+1})$). This distribution vividly shows that the stiffness of the neighboring joists significantly affects the maximum joist stress response. With the highest joist variation considered (40 percent), the most highly stressed joist was sometimes three or more times as stiff as the average of the two adjacent joists.

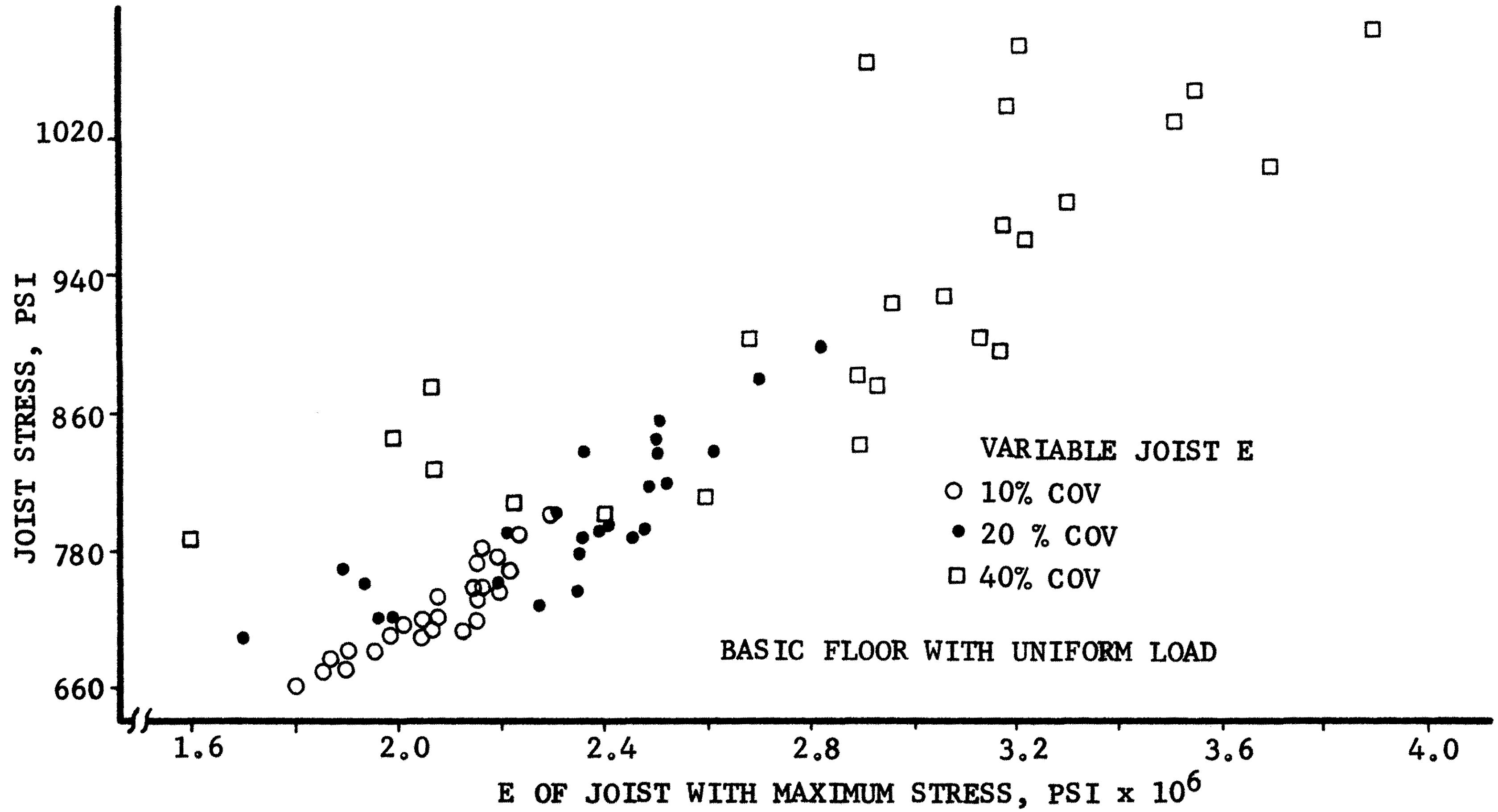


FIGURE 3.19

E OF JOIST WITH MAXIMUM STRESS VS. MAXIMUM JOIST STRESS - SIMULATIONS 1,2 AND 3

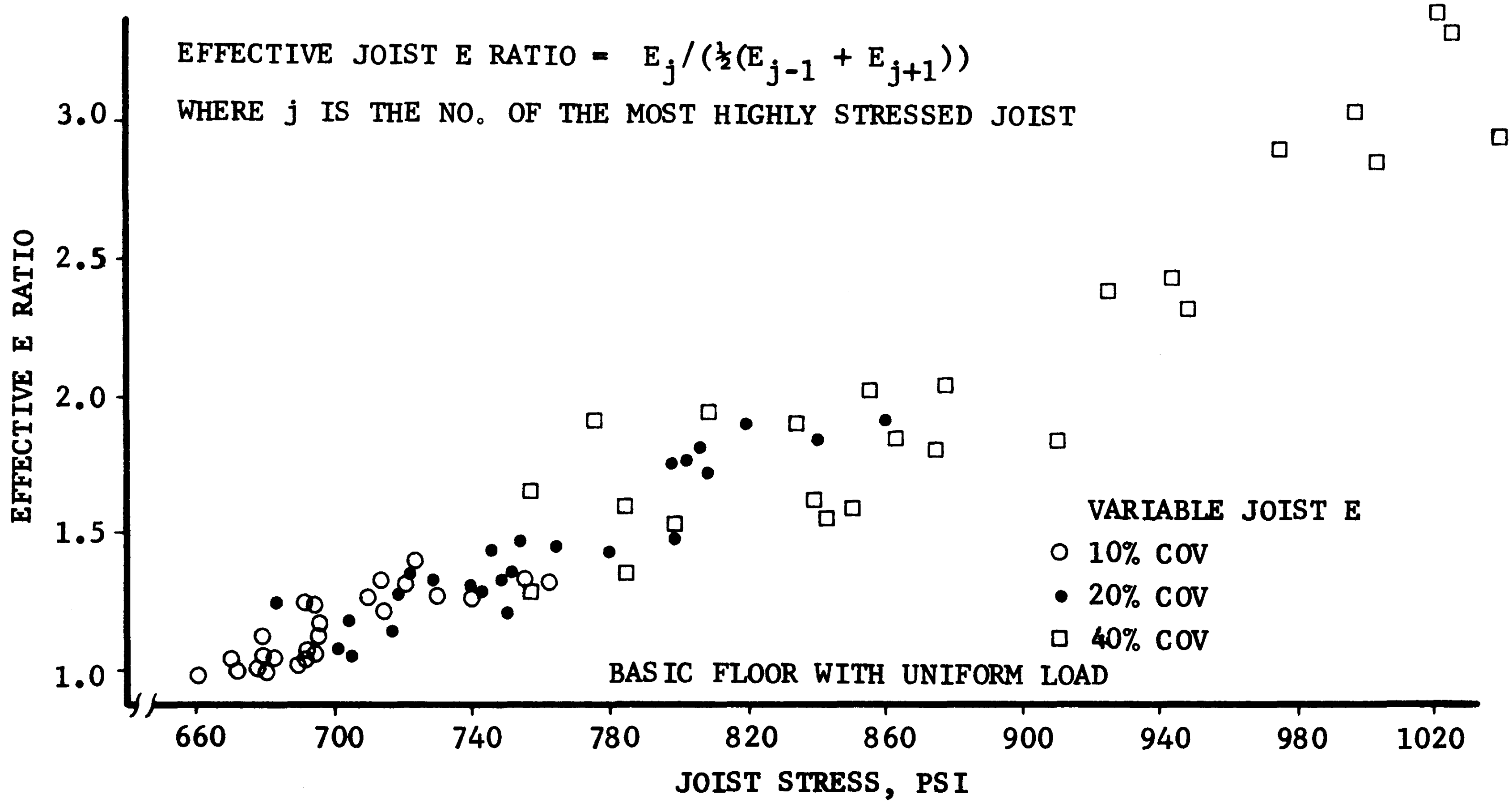


FIGURE 3.20
MAXIMUM JOIST STRESS VS. EFFECTIVE JOIST RATIO - SIMULATIONS 1,2 AND 3

This chapter has shown that under a uniform load the joist E variation is the most significant component in determining the variability of maximum deflections, joist tensile stresses and nail forces. The joist E variation is also the most significant component in determining mean maximum deflection and joist stress. Also it has shown that most floor response characteristics caused by variable material properties can be approximated by considering only the joist E variation. Increased variation of any component is seen to raise the mean maximum response as well as the variability of the response. The deflections in almost every floor simulated are less than the joist-only deflection computed using the mean E value.

It should be noted that the stiffness of the sheathing joints was held constant for all the simulations reported in this volume, including those for the basic floors included in this chapter. Other studies subsequent to the planning of the simulations reported herein have shown that the sheathing joint condition (open versus tightly-butted or glued) and the corresponding joint stiffness values can have a very appreciable influence on floor response and component stresses. Sheathing joint stiffness was not chosen as a variable in this study, at least in part because little information is available on suitable stiffness values and the variability of joint stiffness values has not been determined.

Chapter IV

EFFECTS OF LOADING TYPE AND FLOOR GEOMETRY

4.1 Variations of the Basic Floor System

The second objective of this study was to determine changes in the basic floor response resulting from some changes in floor component geometry and floor loading conditions. For this purpose, simulations of floors having the properties shown in Table 4.1 were conducted.

These simulations are separated into the following three categories:

1. Effect of concentrated loads (Simulations 7, 8 and 9)
2. Effect of butted plywood joints (Simulation 10)
3. Effect of plywood thickness (Simulation 11)

The basic floor properties and cutoff values described in Section 3.1 were used throughout this chapter. The floor configuration, including plywood pattern, shown in Fig. 3.1 was used throughout this chapter. To determine the influence of component stiffness variability on the response of floors with concentrated loading, three simulations were conducted each with only one of the components allowed to vary in stiffness. Levels of coefficient of variation (COV) used were: joist E, 20 percent; plywood E, 20 percent; and slip modulus, 60 percent. Therefore Simulations 7, 8 and 9 were statistically the same as floors 2, 4 and 5, respectively, except for the loading condition.

The concentrated load used in Simulations 7, 8 and 9 was 550 pounds applied at the midspan of the middle joist. This load acting at the midspan of an isolated joist of mean stiffness causes a deflection of 0.399 inches or span divided by 358, near the span over 360 value. (The span divided by 360 value was chosen as a value often seen in design, not as necessarily the proper value for concentrated loads).

TABLE 4.1 Material and Geometric Variability

Simulation Number	Mean Joist E PSI x 10^{+6}	COV Joist E Percent	Mean Plywood E*, PSI x 10^{+6}	COV Plywood E, Percent	Plywood Thickness Inches	Plywood Connection Type	Mean Slip Modulus lbs/in.	COV Slip Modulus Percent	Loading Pounds
7	1.800	20.0	1.360 ∥ 0.529 ⊥	0	0.75	T&G	30,000	0	550 C.P.
8	1.800	0	1.360 ∥ 0.529 ⊥	20.0	0.75	T&G	30,000	0	550 C.P.
9	1.800	0	1.360 ∥ 0.529 ⊥	0	0.75	T&G	30,000	60.0	550 C.P.
10	1.800	20.0	1.360 ∥ 0.529 ⊥	0	0.75	BUTTED	30,000	0	40 PSF
11	1.800	20.0	1.360 ∥ 0.529 ⊥	10.0	0.50	T&G	30,000	40.0	40 PSF

∥ = Parallel E Value for Flexure
⊥ = Perpendicular E Value for Flexure
T&G = Tongue and Groove Connection
COV = Coefficient of Variation
* = Using Gross Untransformed Section
PSF = Pounds per Square Foot
C.P. = Concentrated Load at Floor Center Point

Joint element stiffness (for joints in either direction and for both axial load and bending)

Simulation 10	Butted	500 psi
Others	T & G	10000 psi

The effect of a butted (versus tongue and groove) plywood joint condition on floor response was determined with a simulation of floors having variable joist E and the material properties shown for Simulation 10 in Table 4.1. A uniform load of 40 psf was used for these floors. The maximum floor deflections, tensile joist stresses and nail forces of this simulation can be compared with those of floor Simulation 2 because the properties and level of joist stiffness variation are the same for both. The butted plywood joint was accounted for by using a lower material stiffness for the finite element representing the joint than that used for the tongue and groove connection. Both the tongue and groove and the butted joints were assumed to have an effective width of 1/16 in. and the stiffnesses given in Table 4.1.

The effect of changing the plywood thickness (with all other properties of the basic floor held constant) was simulated using a half-inch plywood thickness in Simulation 11. A comparison of the results from this simulation with those of Simulation 6, which included floors statistically the same except for the plywood thickness, and the deflections computed for joist only can supply adequate data for describing an approximate relationship between plywood thickness and floor response.

4.2.1 Simulations with Concentrated Loading

Floor Simulations 7, 8 and 9 were conducted with the material properties and variations given in Table 4.1. Figures 4.1 and 4.2 show the resulting cumulative maximum floor deflections and maximum joist tensile stresses within each floor for simulations with variable joist E of 20 percent COV (Simulation 7). These distributions show that the center of each response distribution is located

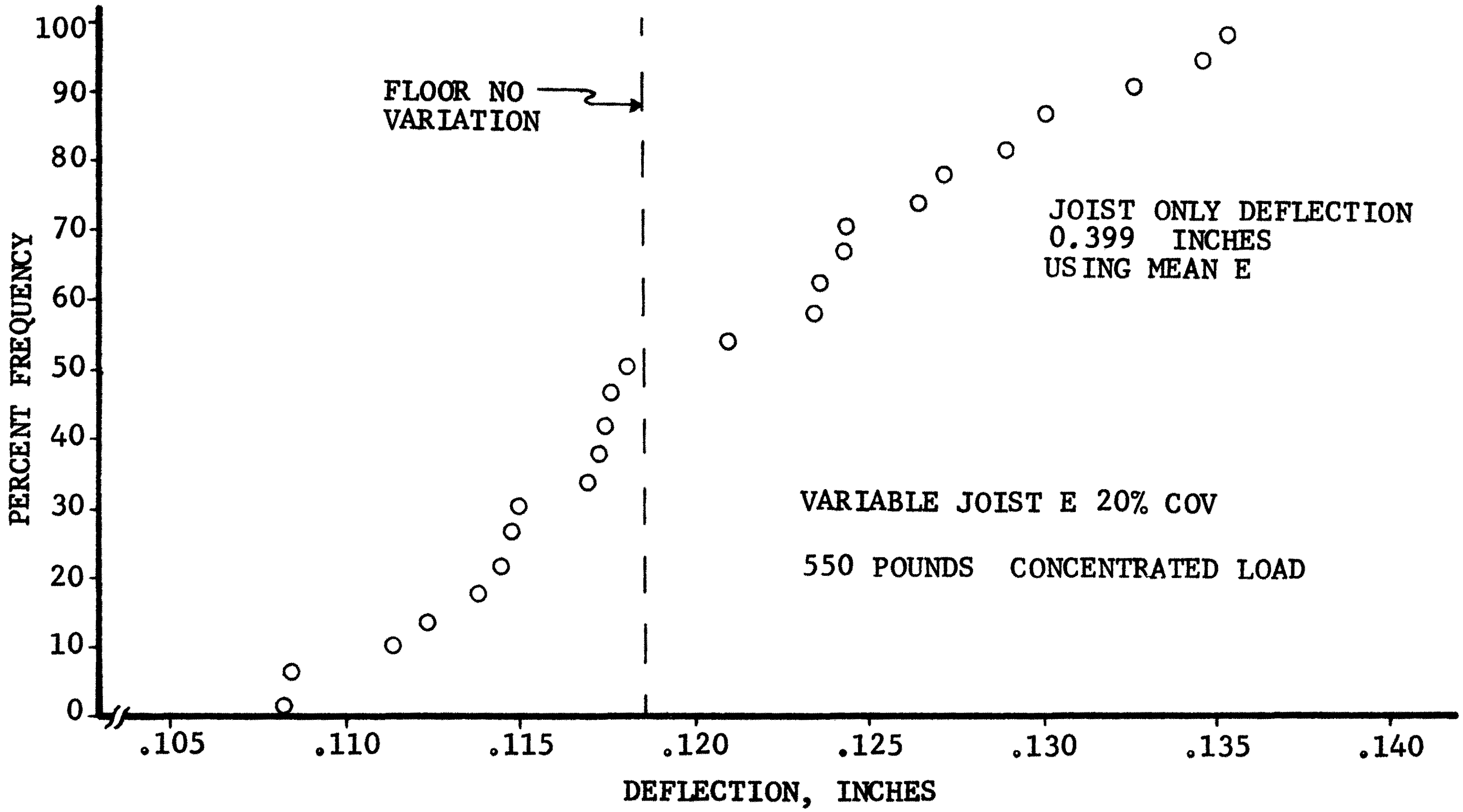


FIGURE 4.1

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 7

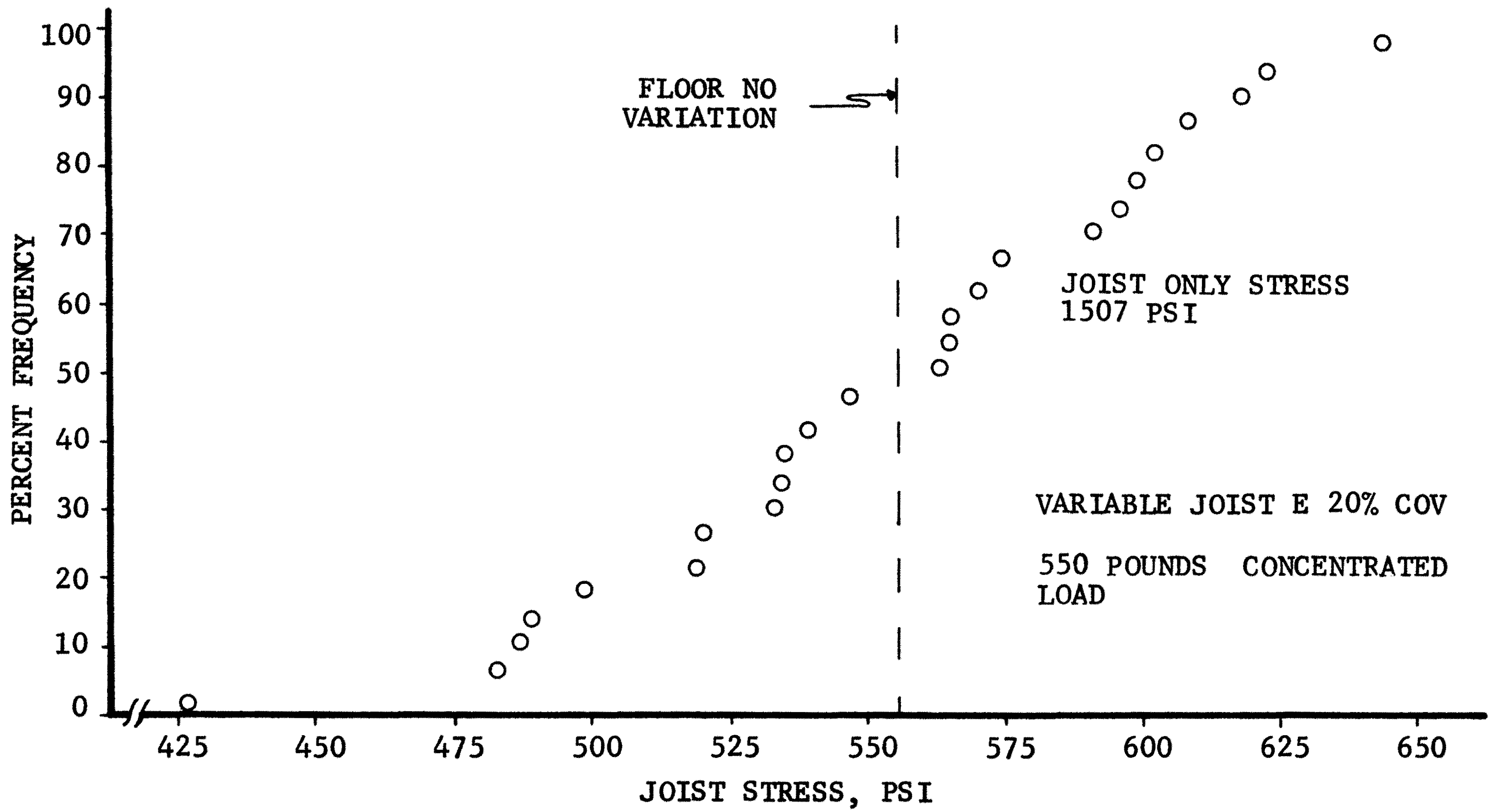


FIGURE 4.2

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 7

approximately at the value computed for the floor without material variability. This type of response should be expected. In all floors, the loaded joist was always the location of the maximum deflection and joist stress. Consequently, the critical joist location was set by the loading condition and this critical joist would have an above average stiffness for about one half of the floors. The adjacent joists act to share the load. The deflections and stresses depend on both the loaded joist stiffness, which influences the load distributed laterally, and the adjacent joist stiffnesses, which determines their ability to support these loads. The simulated floor deflections are compared to joist-only deflections in Fig. 4.3. It can be seen that a considerable decrease in deflections occurs when component interaction is incorporated. The distribution curve for the floor system has values approximately 30 percent of those for the joist only, which indicates that about 70 percent of the load was distributed laterally to other joists.

The cumulative distributions of maximum joist deflection and joist stress among the floors for the simulations of concentrated loaded floor with variable plywood E are given in Figs. 4.4 and 4.5. The maximum deflection and joist stress of the floor with no variation in material properties is again located at about the center of each distribution. The range of maximum deflections resulting with a 20 percent COV for the plywood E are close to those for the same level of joist stiffness variation; compare Figs. 4.1 and 4.4. Joist tensile stresses vary slightly less with plywood variability. Therefore, the variability of plywood E has a more significant effect on the response variation of concentrated-loaded floors than for the uniform loading case.

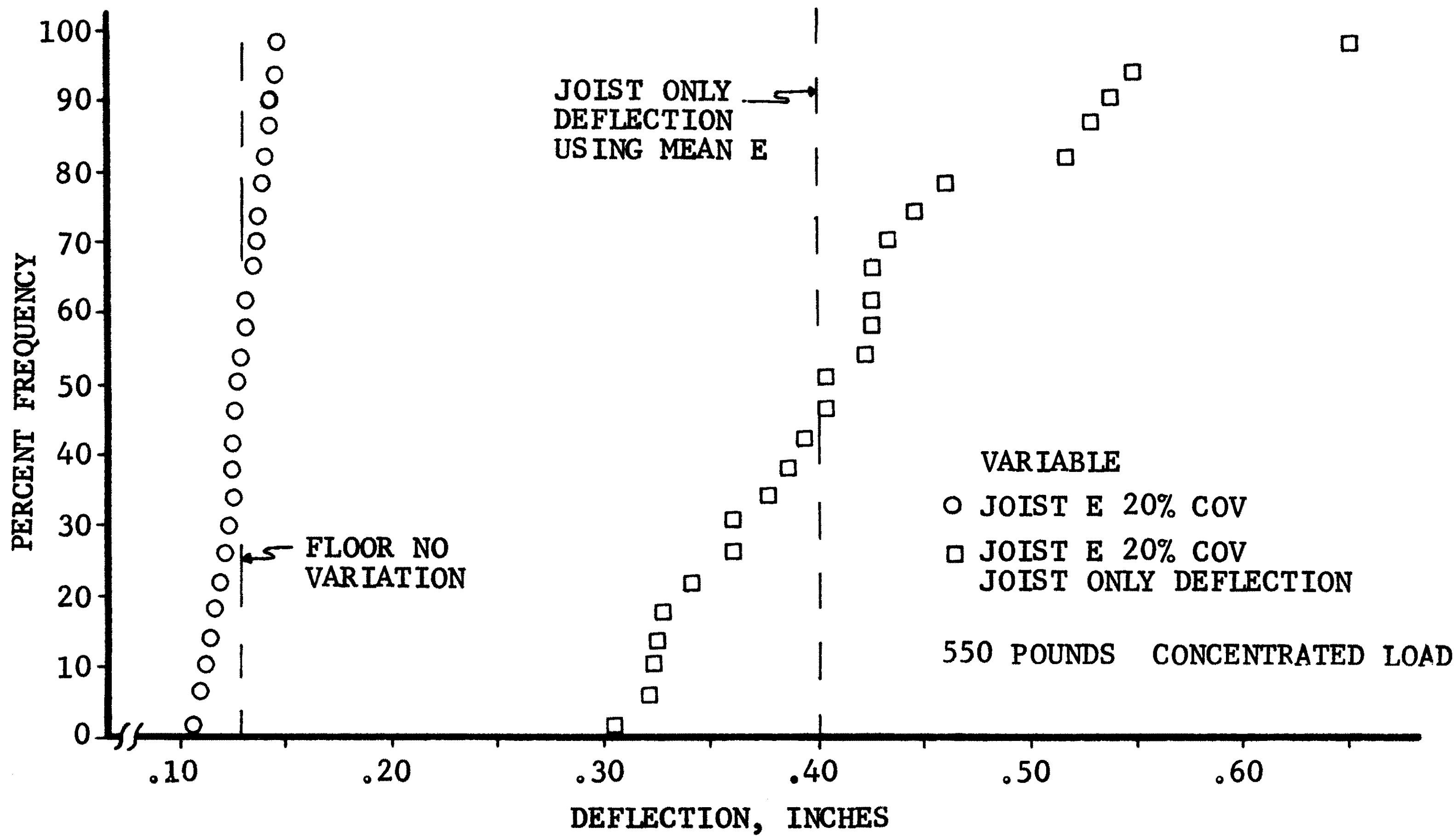


FIGURE 4.3

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 7

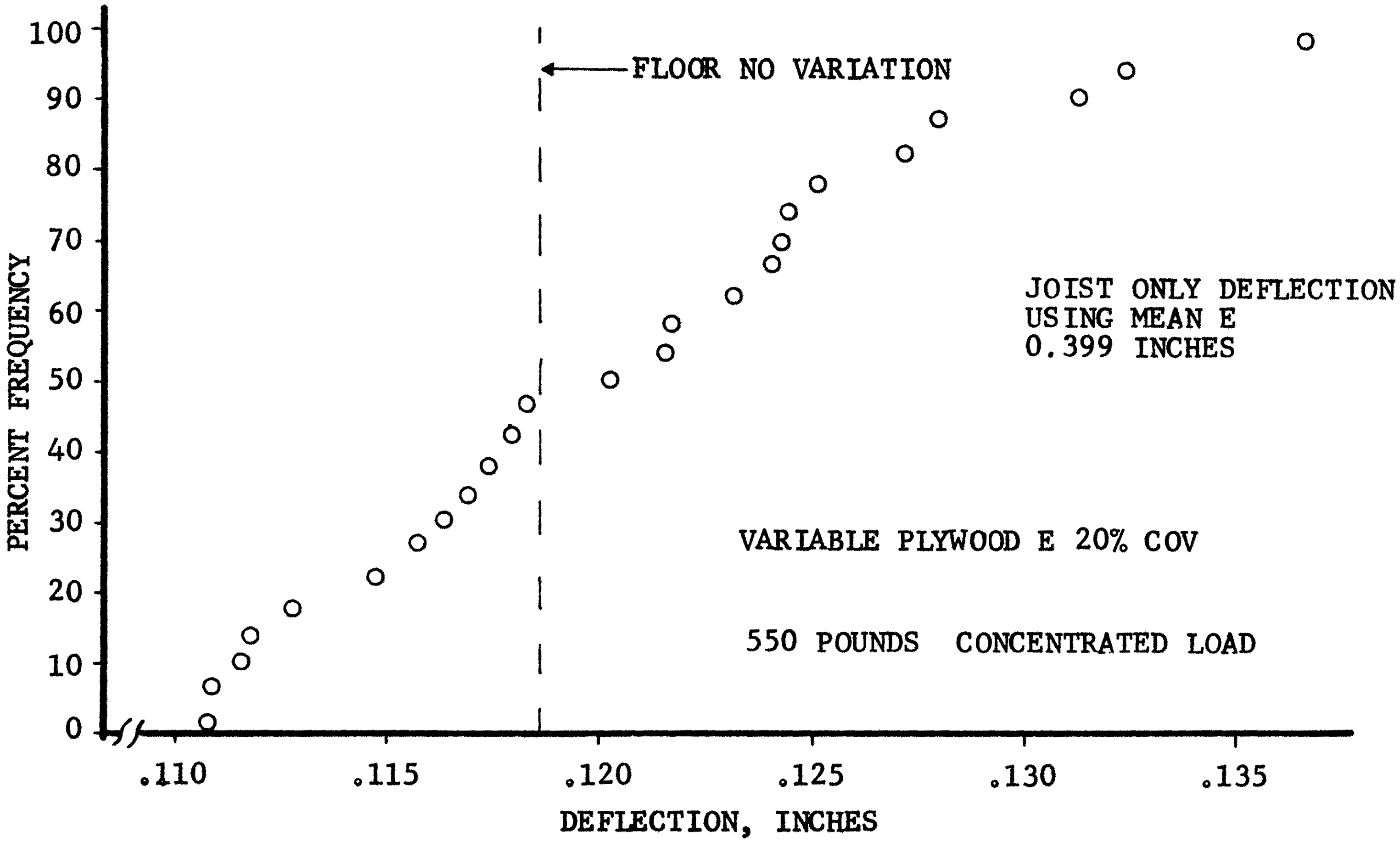


FIGURE 4.4

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 8

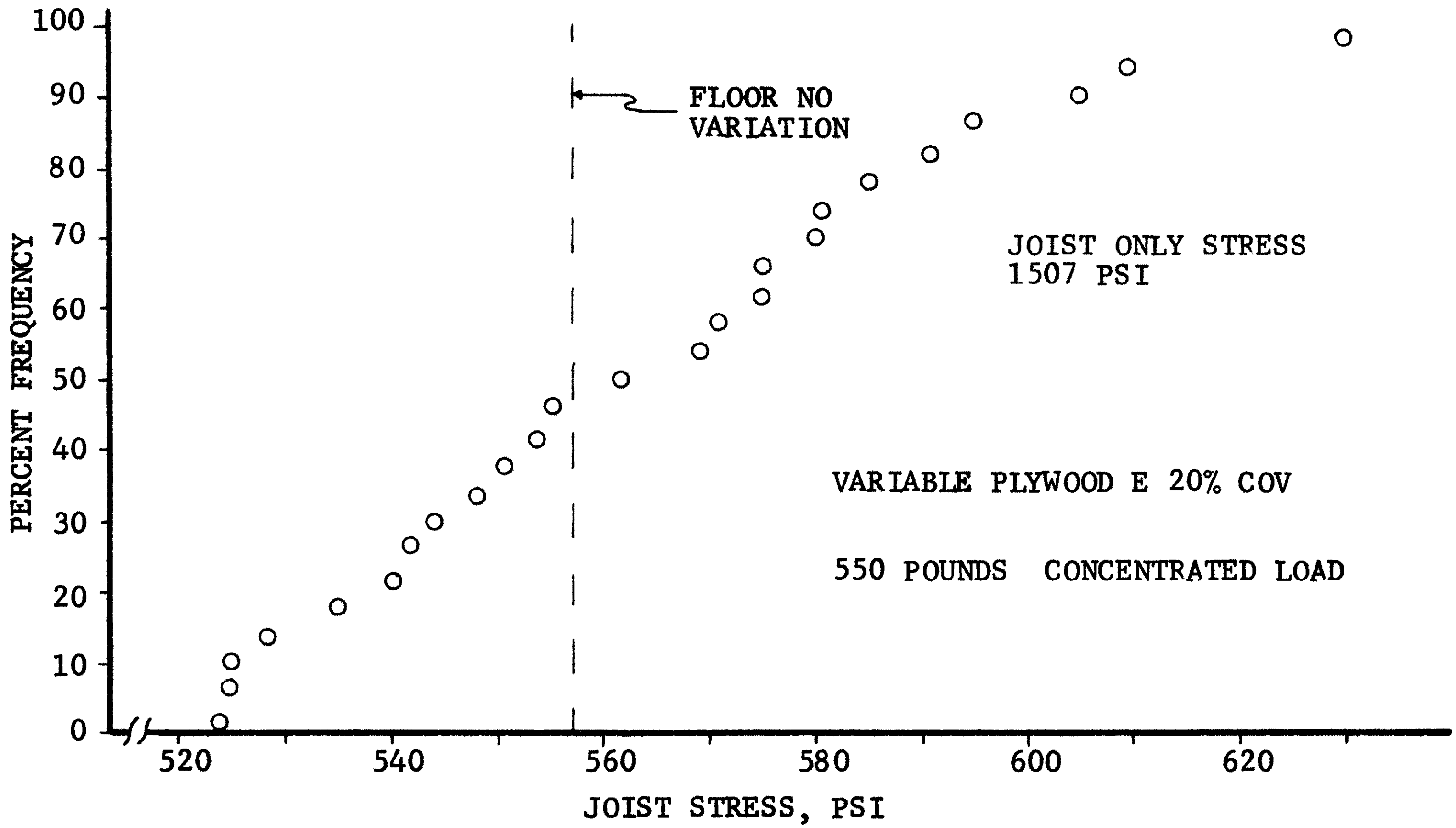


FIGURE 4.5

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 8

Figures 4.6 and 4.7 show the cumulative maximum deflection and joist stress distribution for the basic floor with variable slip modulus, again with a concentrated load of 550 pounds acting at the center of the floor, Simulation 9. The range of maximum deflections and joist stresses are approximately the same as in Simulations 7 and 8 (variable joist E and plywood E with a concentrated load). However, the variation of slip modulus was three times greater (60 percent vs. 20 percent) than that for either the joist E or plywood E coefficient of variation. Therefore, the slip modulus variability does not produce as significant variations for maximum deflection and joist stress as do the other two variabilities investigated. The values for maximum floor response distributions when slip modulus is varied are again clustered around the no-variation values.

4.2.2 Simulations Varying the Plywood Joint Condition

The condition of the joints in the plywood sheathing layer was found to have a significant effect on the floor response.

Figures 4.8 and 4.9 show the distributions of maximum joist deflection and joist tensile stresses within each of the twenty-five floors of Simulation 10. The basic floor configuration with butted plywood joint conditions and a uniform load of 40 psf was used. Except for the joint condition specified, Simulation 10 had the same specifications as did Simulation 2. Figure 4.8 shows a range of maximum deflection values approximately equal to that of Fig. 3.2 of Simulation 2. However, the maximum deflection and joist stress values are higher by approximately 16 percent and 10 percent respectively, in the butted plywood system than in the tongue and groove plywood system.

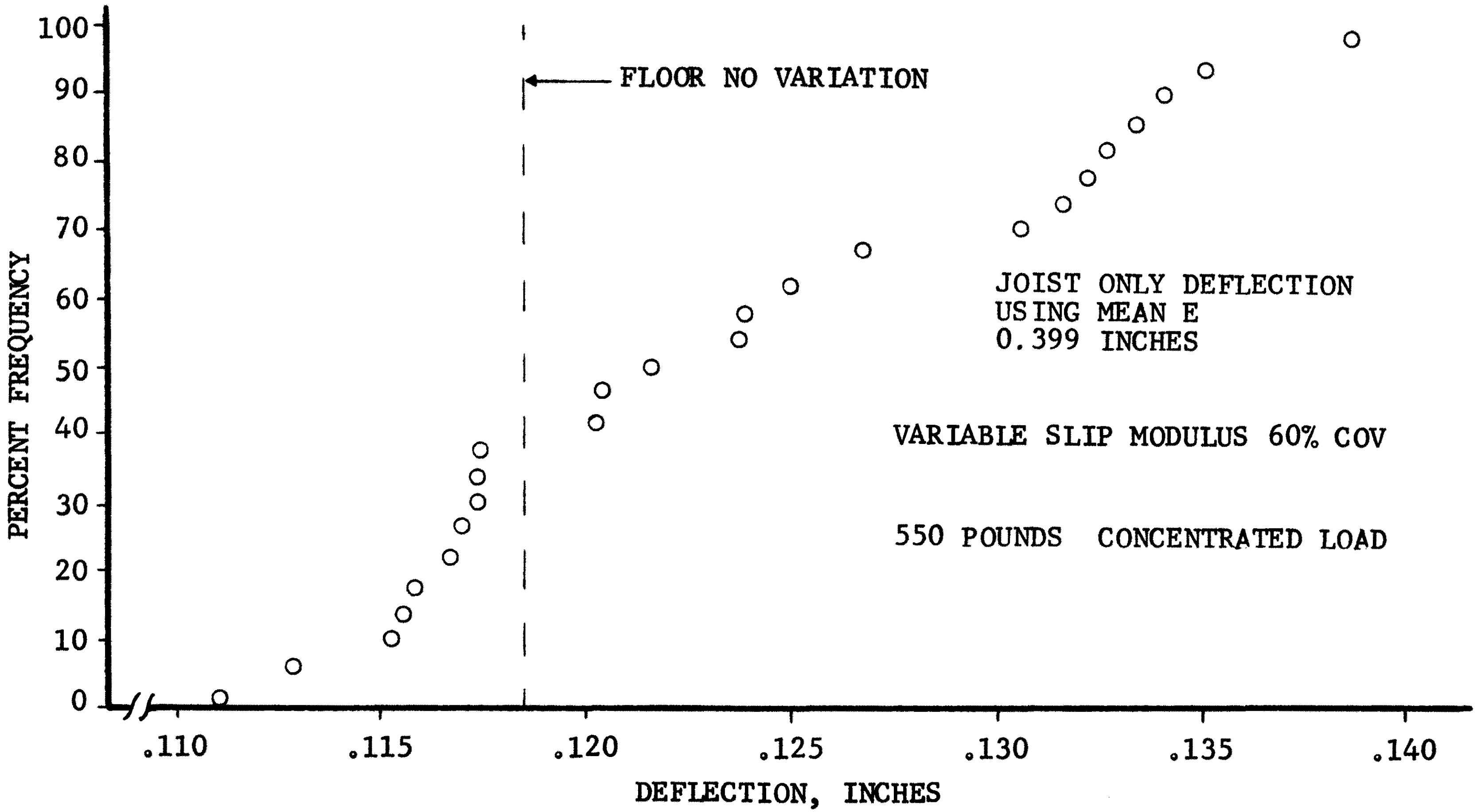


FIGURE 4.6
CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 9

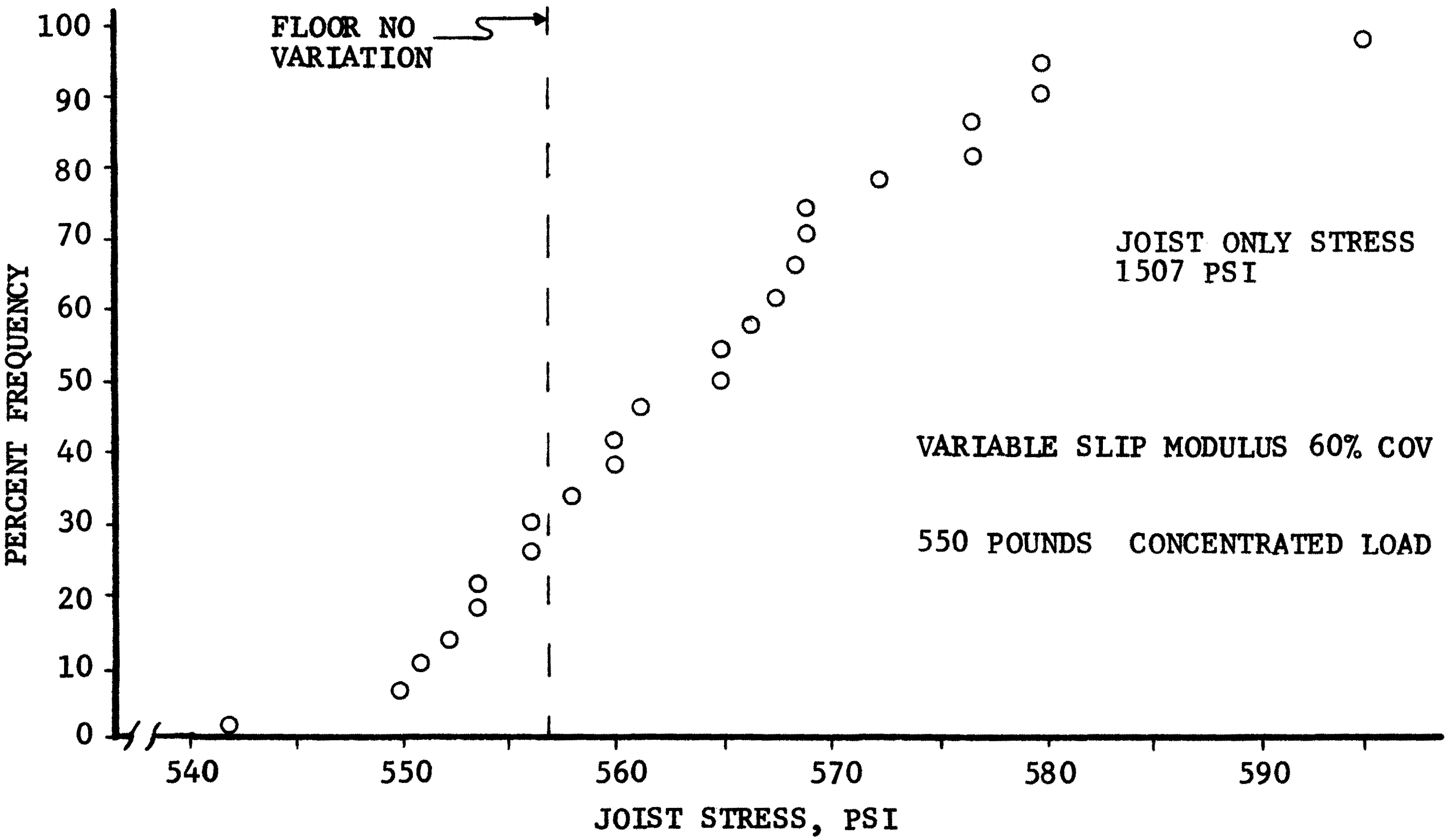


FIGURE 4.7

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION

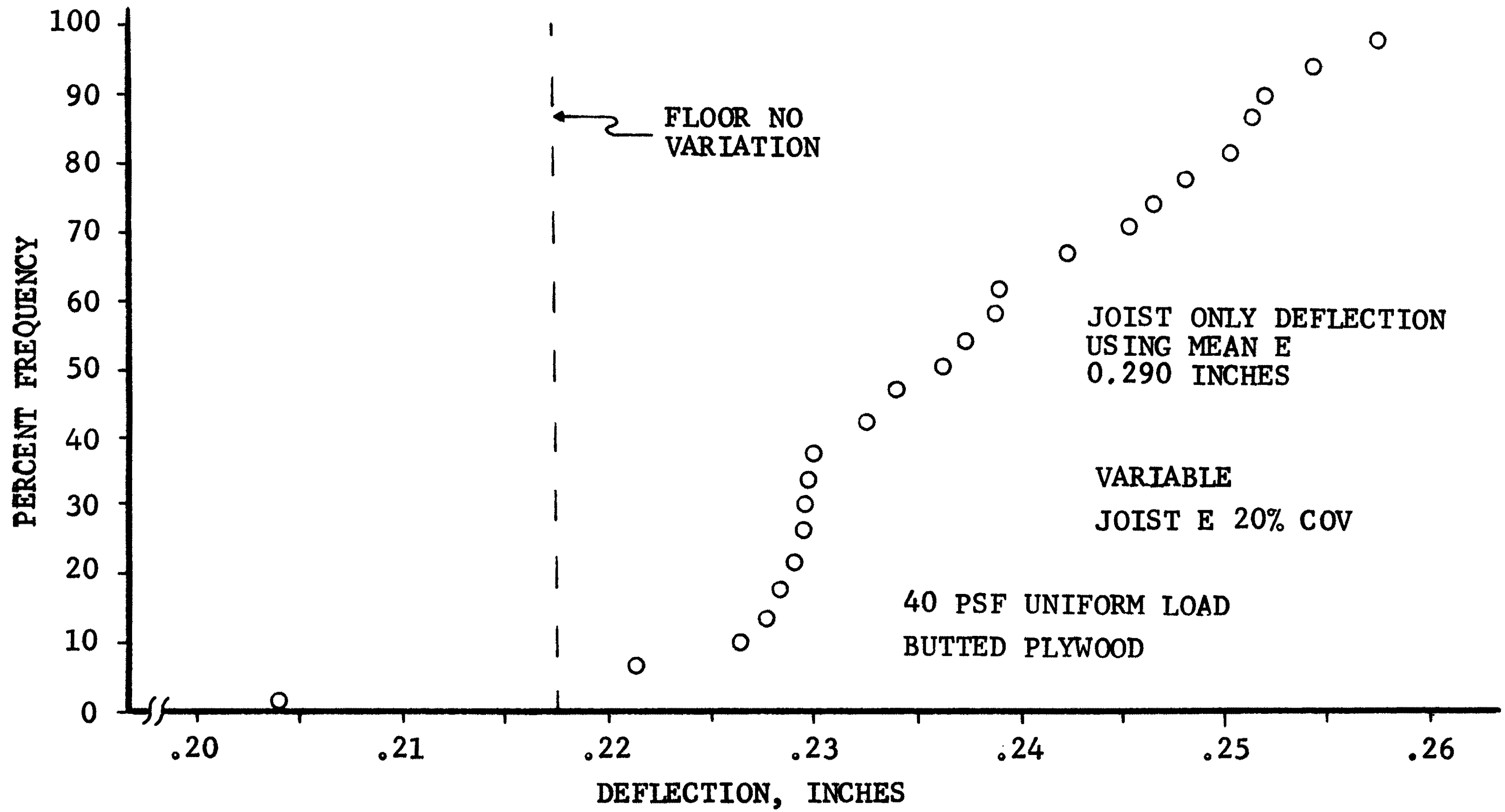


FIGURE 4.8
CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 10

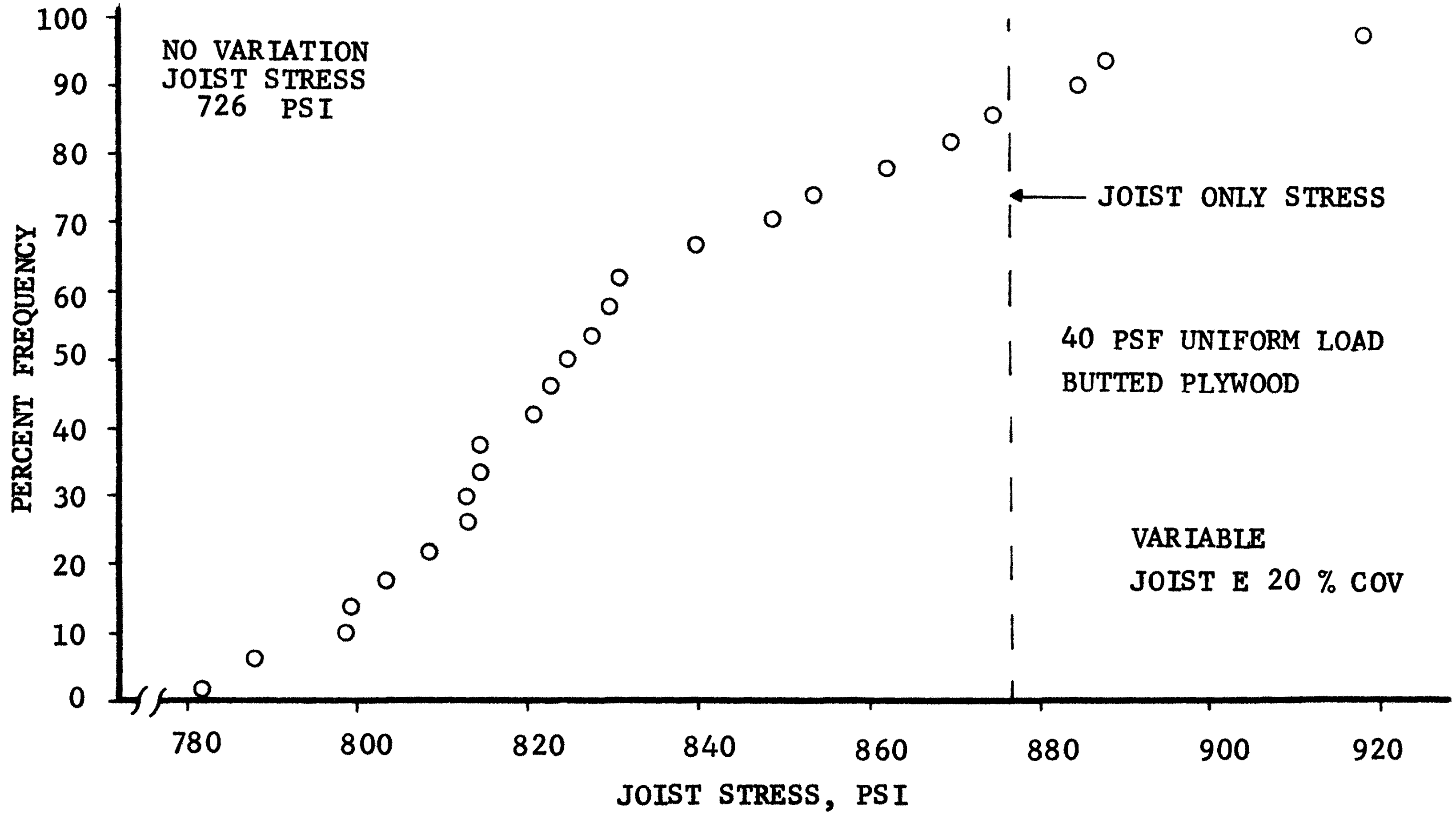


FIGURE 4.9
CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 10

Figure 4.10 shows the deflection reduction obtained by considering the butted plywood floor system as an integral unit and as a system of isolated joists without sheathing. Figures 4.8 and 4.10 show that the maximum floor deflection value can be less than the maximum deflection value of the same floor with no variability. This is possible if the randomly selected floor has been assigned components with a relatively high sample mean and a low sample COV.

4.2.3 Effects of Changing Plywood Thickness

Decreased plywood thickness will result in less floor stiffness and a greater influence of joist properties on the floor response. To quantify these behaviors, Simulation 11 was conducted. The floors in this simulation were the basic floor with a one-half inch thick plywood sheathing layer substituted for the 3/4 in. thickness specified for the floors of Chapter III. A uniform load of 40 psf was used. The same mean component stiffnesses and variabilities as had been used with Simulation 6 (20 percent with joist E, 10 percent with plywood E and 40 percent for slip modulus) were specified in Simulation 11. The cumulative distribution of maximum joist deflections and joist tensile stresses within each floor of Simulation 11 are shown in Figs. 4.11 and 4.12. Both of these distributions show values higher than Simulation 6 (3/4 inch plywood thickness). The ranges of the distributions are slightly reduced with the thinner plywood. These approximately ten percent and seven percent increases in joist deflections and joist tensile stresses for Simulation 11 reflect the expected influence of the decrease in plywood thickness. However, all the maximum floor deflections in Simulation 11 are still below the 0.290 in. joist only deflection computed with the mean joist E.

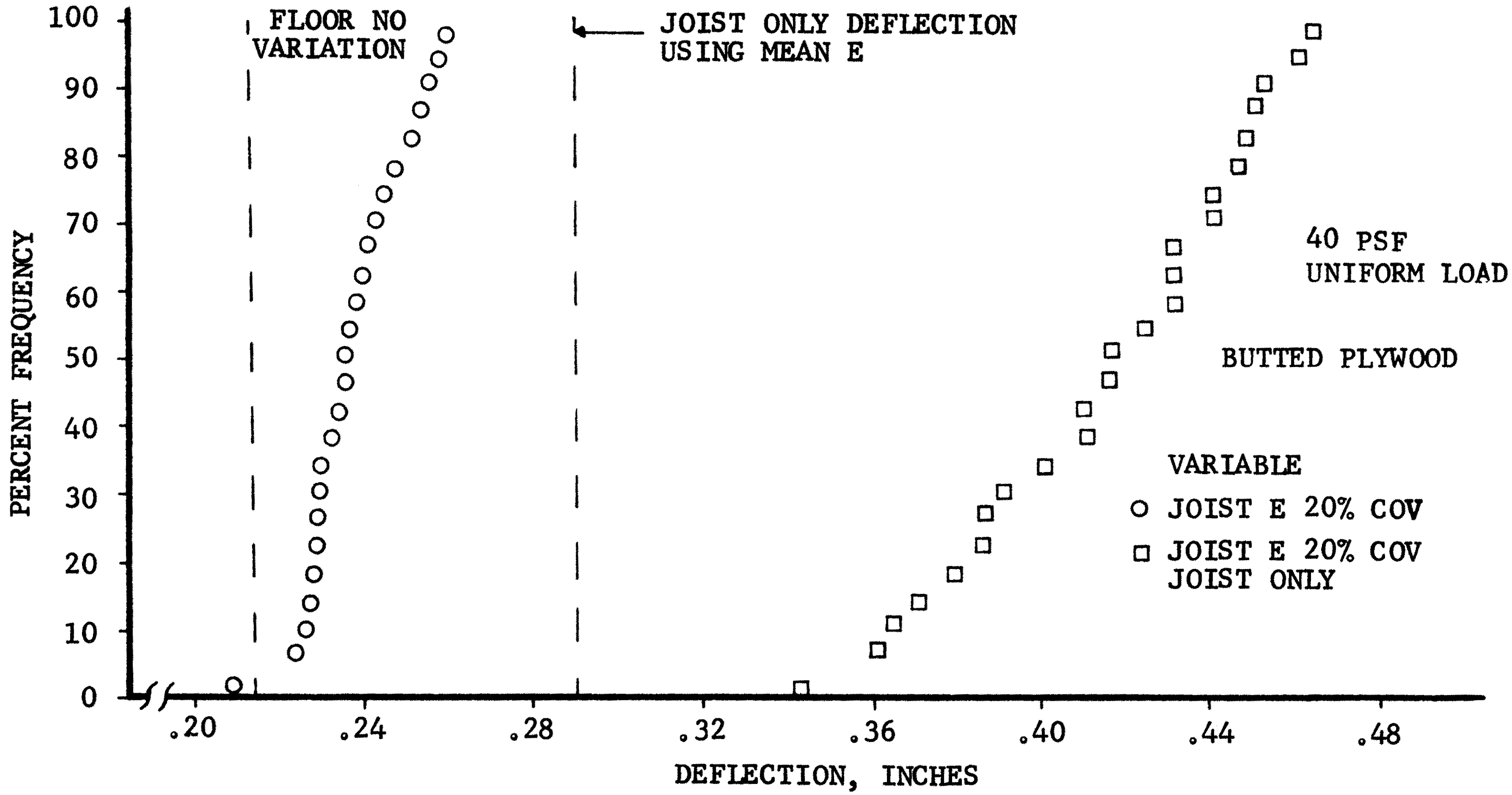


FIGURE 4.10

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 10

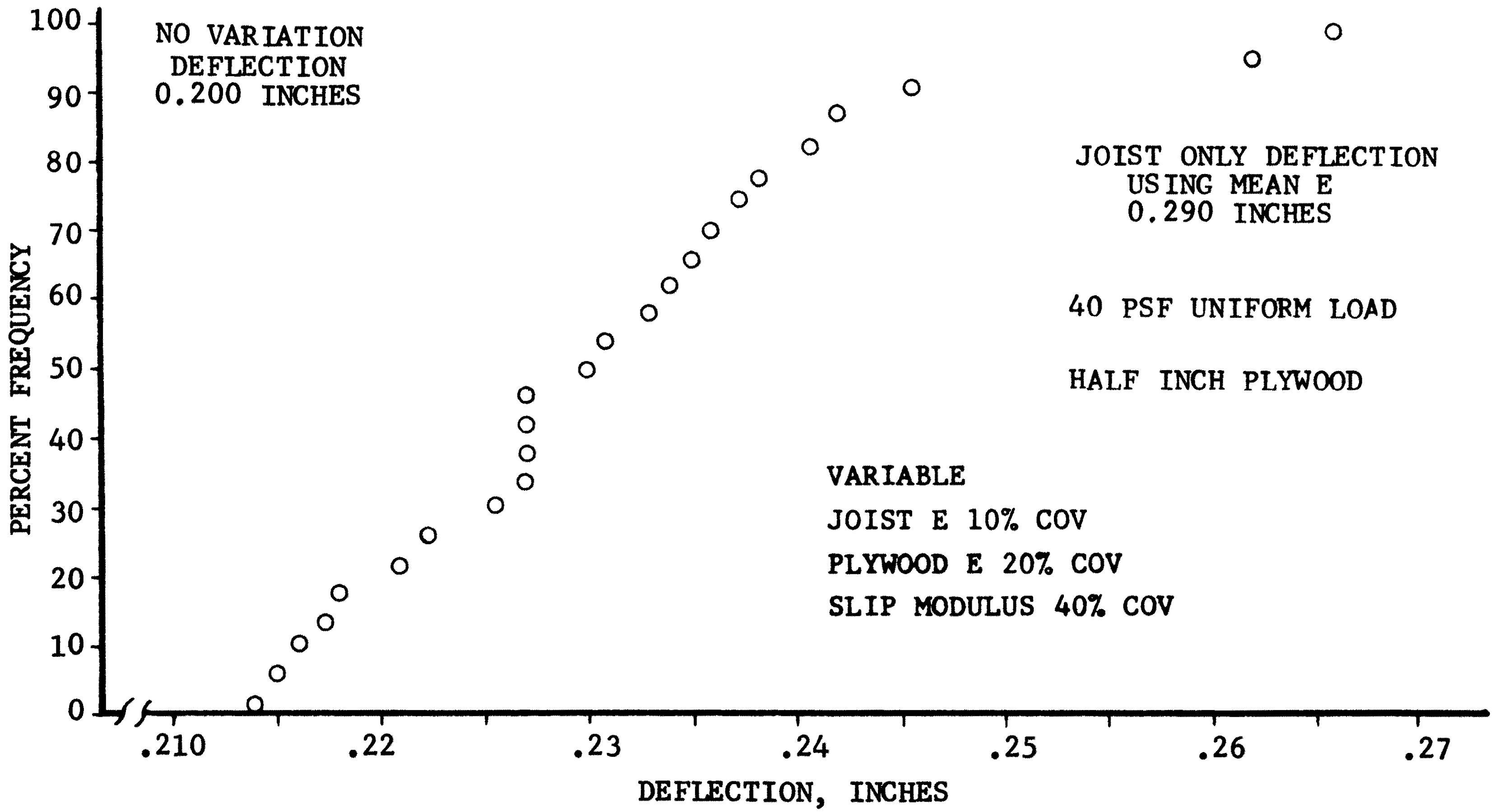


FIGURE 4.11
CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 11

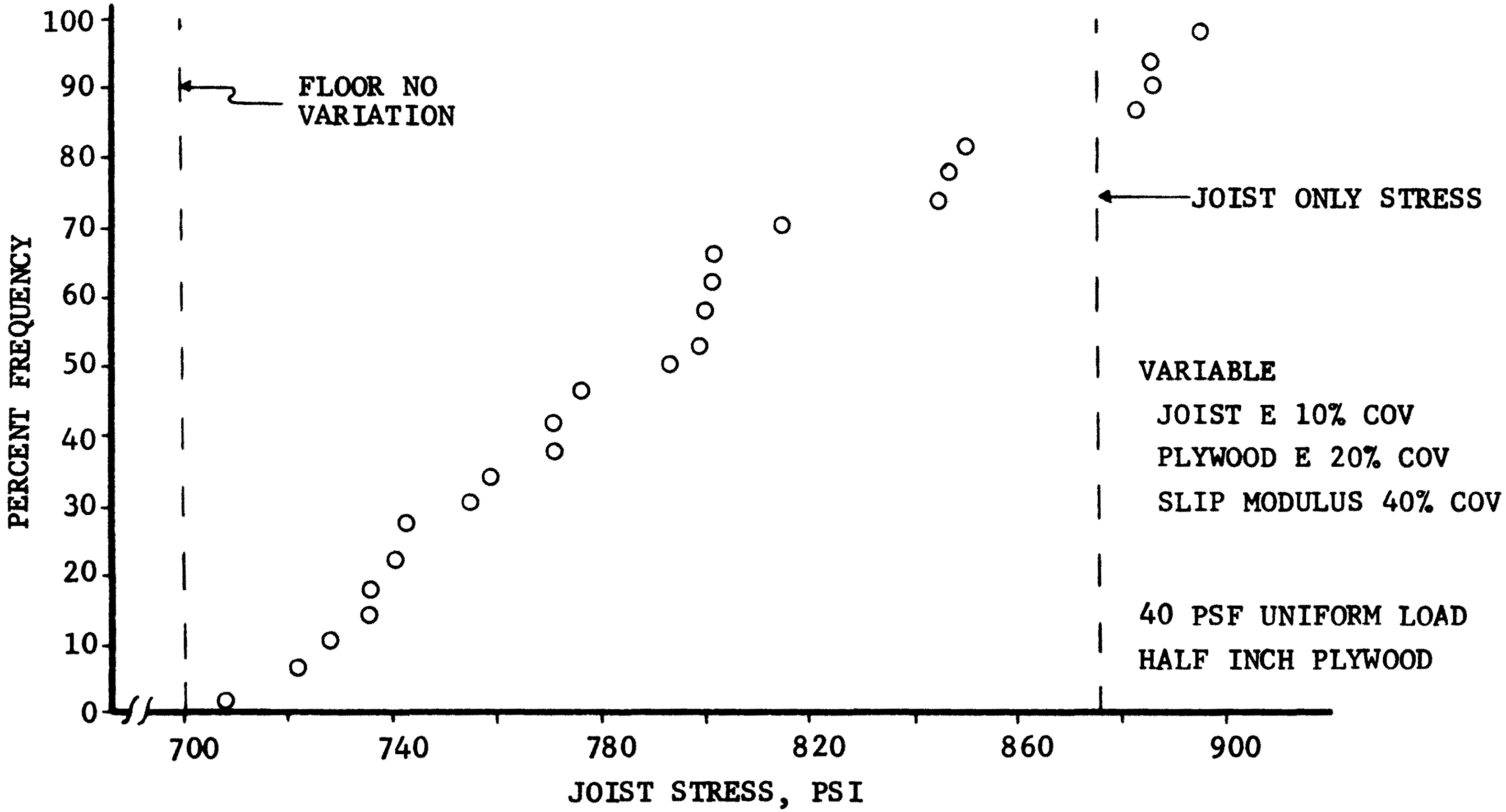


FIGURE 4.12

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 11

4.3.1 Discussion of the Effects of Material Property Variations on Response of Floors with Concentrated and Uniform Loadings

In this section the COV of the component properties of Simulations 7, 8 and 9 presented in Section 4.2.1 are compared with the resulting variations of the floor response with concentrated load (Section 4.2.1) and with the response of the same basic floors uniformly loaded (Section 3.2). Figures 4.13, 4.14 and 4.15 show the maximum deflection COV, maximum joist tensile stress COV and maximum nail force COV as a function of component COV used in Simulations 7, 8 and 9. The assumption of a linear relationship between component characteristics and response characteristics used previously in Section 3.3 will be assumed to be applicable also for a floor with concentrated loads.

The material property component coefficient of variation (COV) values versus the maximum joist deflection COV in Fig. 4.13 shows that under a concentrated load both joist E and plywood E have a large and approximately equal effect on the deflection COV. The variability of the maximum joist deflection (which was always under the loaded joist) was 32.8 percent, 29.7 percent and 10.9 percent of the coefficient of variation of 20 percent for joist E, 20 percent for plywood E and 60 percent for slip modulus, respectively. These relationships are different from those found for the uniform loading case. For uniform loading the joist E variability had a much larger effect than either plywood or connector stiffness. The increased importance of the plywood E variation with concentrated loading can be explained by comparing the typical deflection profile across the joist centerlines of a uniformly loaded floor and that for a floor with a concentrated load. These profile shapes are shown in Appendix C. For the concentrated

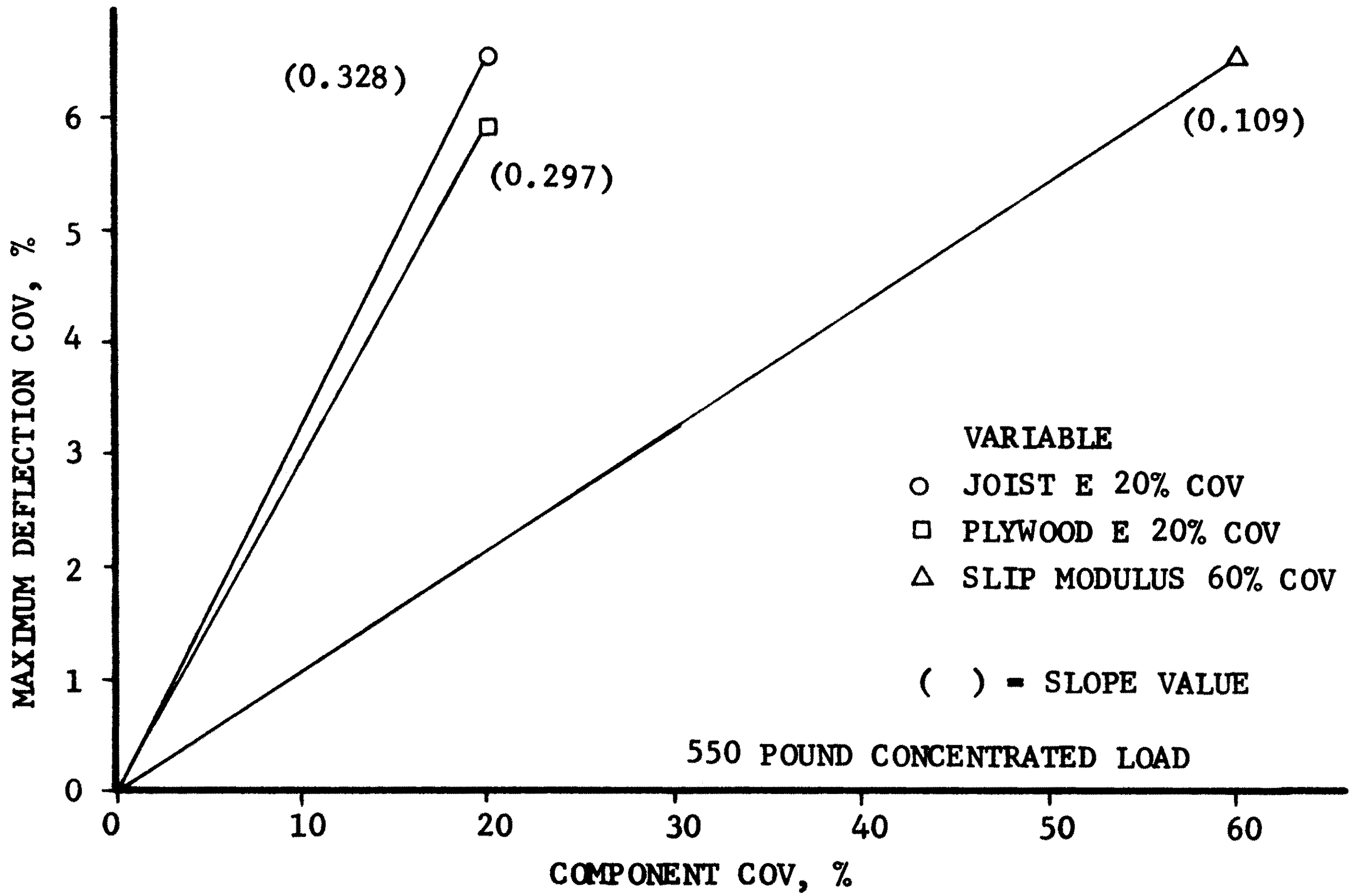


FIGURE 4.13
COMPONENT COV V.S. MAXIMUM DEFLECTION COV - SIMULATIONS 7,8 AND 9

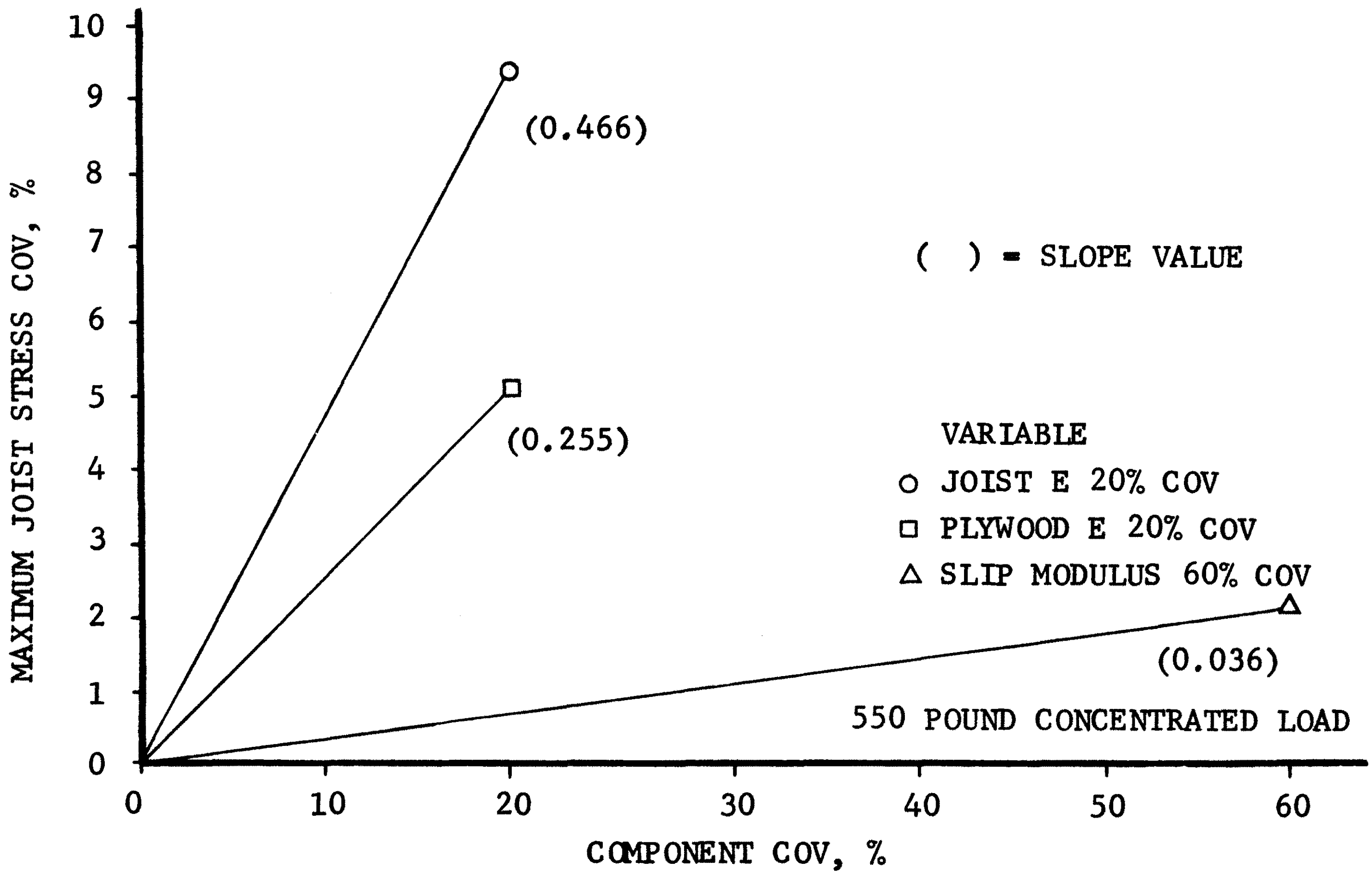


FIGURE 4.14
COMPONENT COV V.S. MAXIMUM JOIST STRESS COV - SIMULATIONS 7,8 AND 9

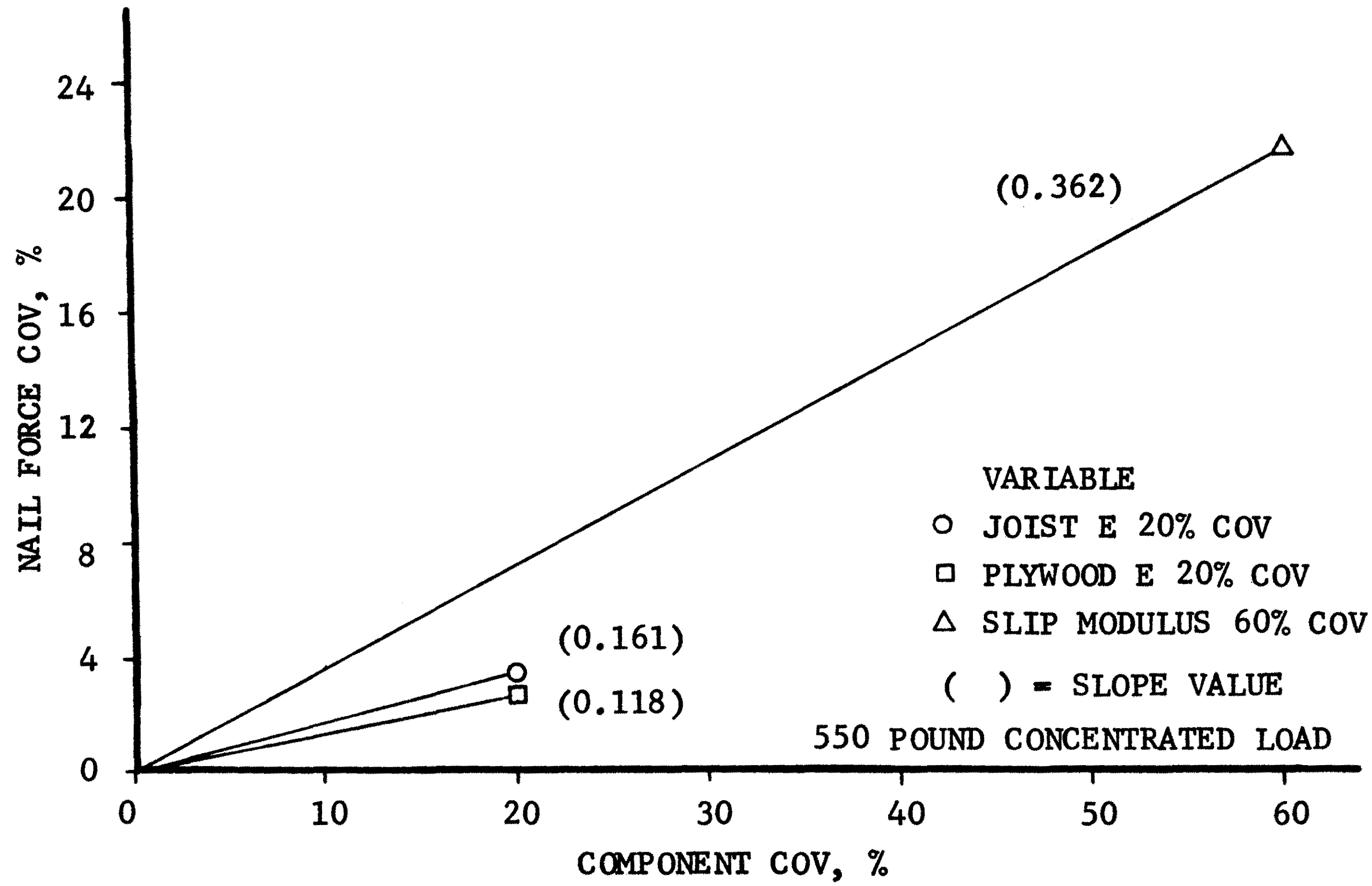


FIGURE 4.15

COMPONENT COV V.S. MAXIMUM NAIL FORCE COV - SIMULATIONS 7,8 AND 9 load the plywood sheathing layer has much higher bending curvatures in the direction perpendicular to the joists. Consequently, variations of the plywood bending stiffness result in larger differences in the sheathing layer flexural stresses for the concentrated loaded case than for a uniform loaded floor with smaller curvatures. For the concentrated load case, a stiffer sheathing layer will be able to relieve more load from the critical joist and thus greatly influence the deflection of this critical joist. The influence of joist variability on maximum joist deflection was nearly identical for the two loading cases. The COV of the maximum joist deflection for the uniformly loaded floors equaled 33.7 percent of the joist E COV versus 32.8 percent with a concentrated load and a joist variation of 20 percent. Joist deflection variation increased from 6.3 percent to 29.7 percent of the plywood variation and from 9.0 percent to 10.9 percent of the slip modulus variation when the loading system was changed from uniform to concentrated load.

The maximum joist tensile stress COV expressed as a function of component COV is present in Fig. 4.14. The joist E variability has the most pronounced effect. Variation of sheathing stiffness again is found to be fairly important, however, not as significant as this sheathing E variation was for joist deflections. For a joist E variation of 20 percent, a joist stress COV of 46.6 percent resulted for a concentrated loading as compared to 28.4 percent of the joist E COV for a uniform loading. Plywood E variability also had a larger effect on joist stress variation for concentrated than for uniform loads. With a plywood E variation of 20 percent, the COV of the maximum joist stress was 25.5 percent of the sheathing stiffness COV for concentrated loading versus 5.1 percent for the uniform loading. The influence of slip modulus COV moved in an opposite effect, being less influential for the concentrated loading case.

Figure 4.15 shows the component COV as a function of the nail force coefficient of variation (COV). The nail slip modulus variation has the greatest effect on computed nail force variation, being over twice as influential as the same COV of joist or plywood E.

Figures 4.16, 4.17 and 4.18 show the effect component variability has on the mean maximum response of a floor system with a concentrated load acting at the center of the floor. The maximum deflection response caused by component COV is shown in Fig. 4.16 to be similarly affected by the variation of all three component stiffnesses. The increased influence of the sheathing stiffness again can be explained by the increased importance of the sheathing flexural action indicated in Appendix C.

The mean values of the maximum joist deflection and tensile stress response are relatively insensitive to the component variability for the concentrated loaded case. This is shown by the greatly expanded vertical scale needed in Figures 4.16 and 4.17. Mean maximum joist deflection increased (from the no-variation case) 0.000113, 0.00010 and 0.0000817 times the joist E, plywood E, and slip modulus COV expressed in percents for the concentrated loaded case versus 0.00010 to 0.0010 slopes for the uniform loading case. Thus, the movement of the mean of the maximum floor deflection response is much lower for the concentrated loading. The smallness of these slope values is more important than their exact values. Slightly different floor samples

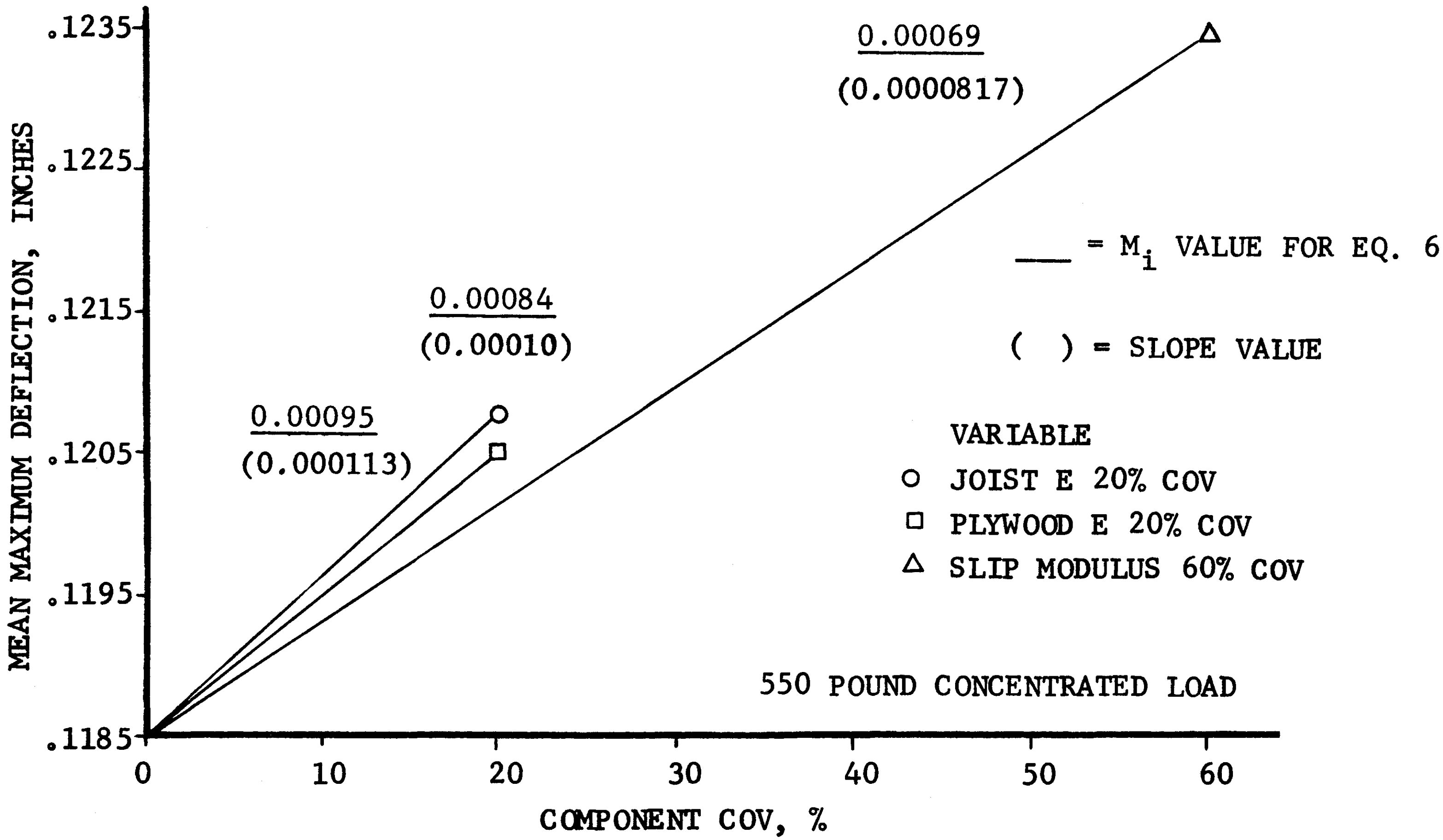


FIGURE 4.16

COMPONENT COV V.S. MEAN MAXIMUM DEFLECTION - SIMULATIONS 7,8 AND 9

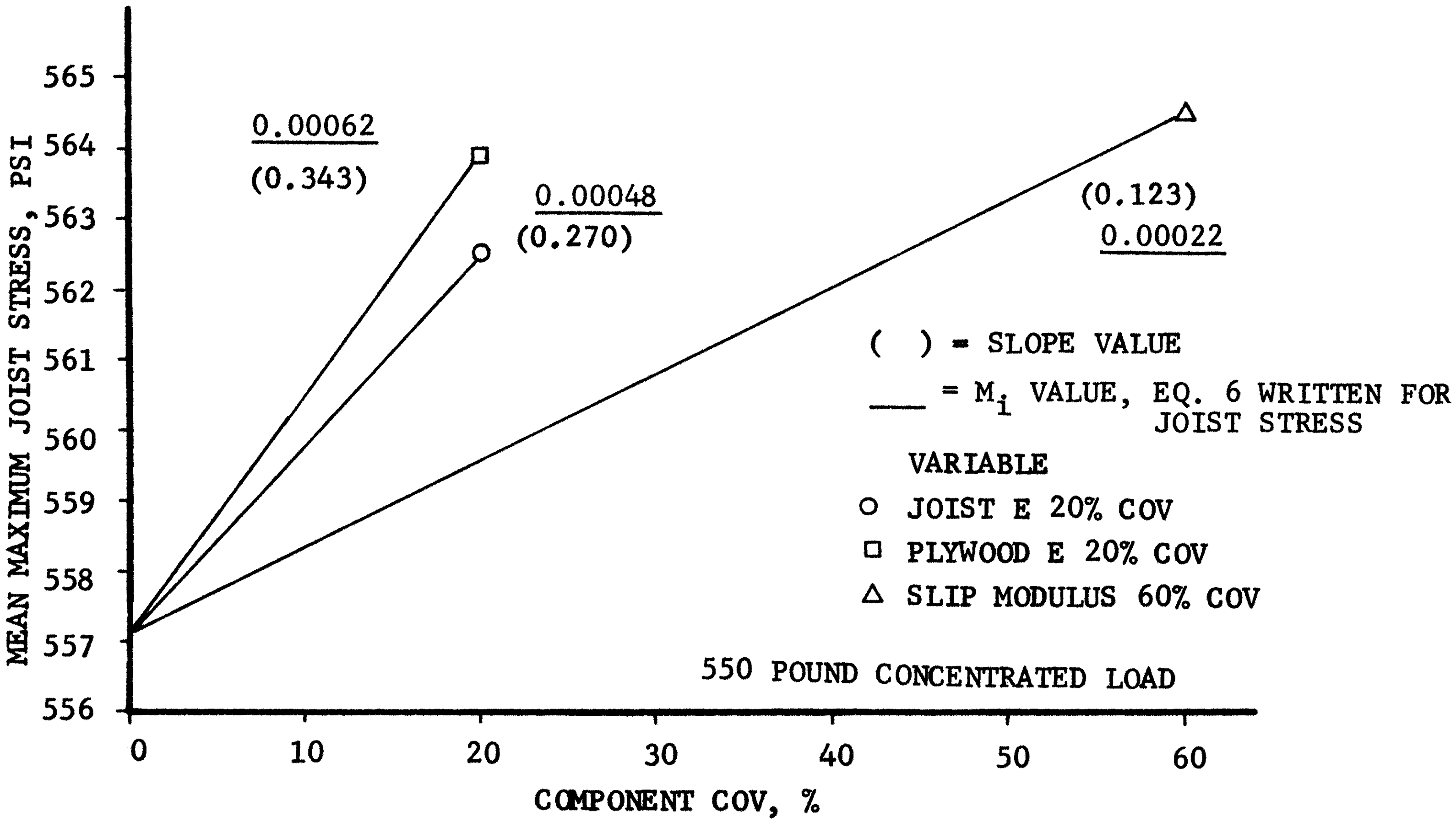


FIGURE 4.17

COMPONENT COV V.S. MEAN MAXIMUM JOIST STRESS - SIMULATIONS 7,8 AND 9

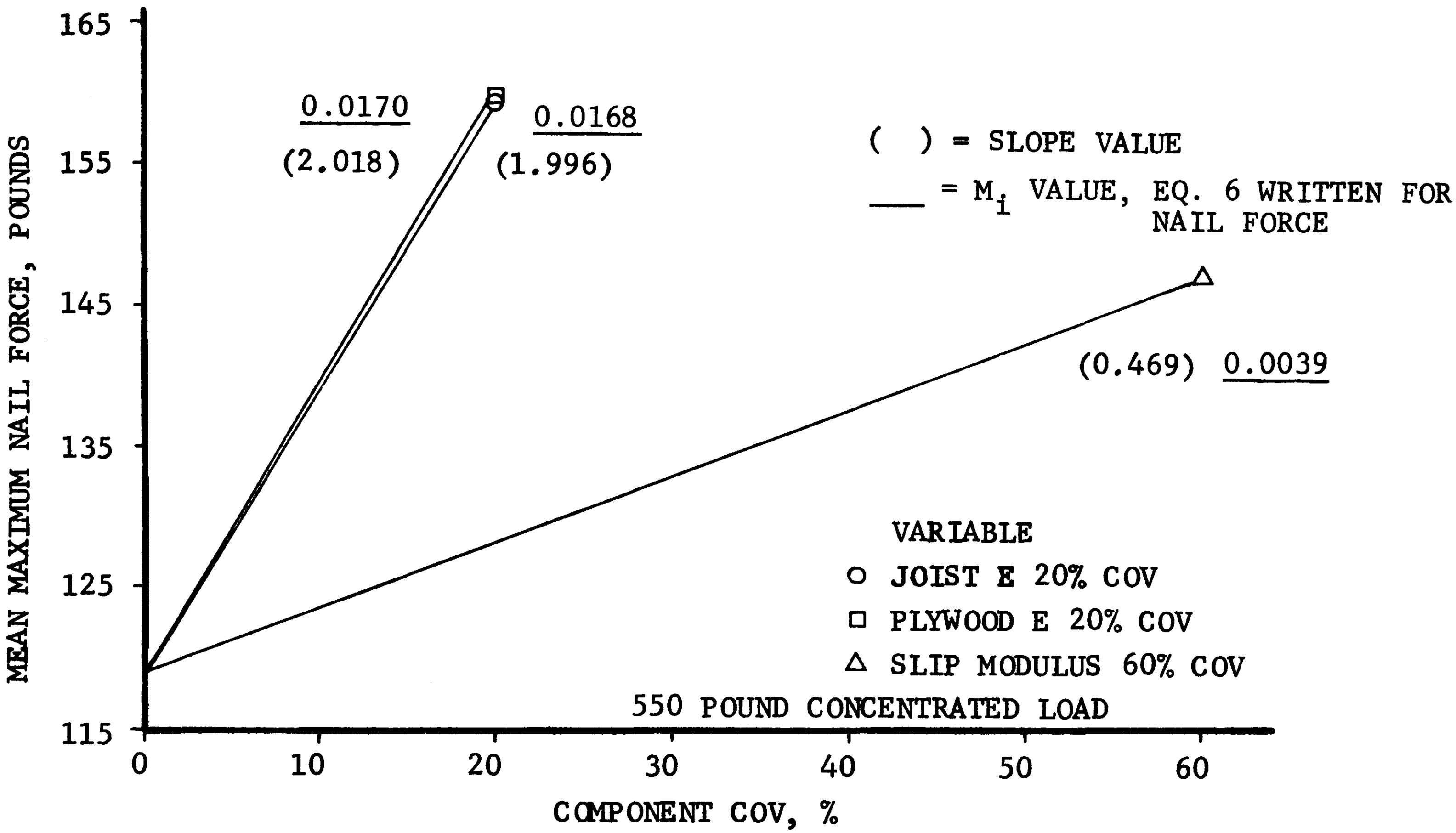


FIGURE 4.18

COMPONENT COV V.S. MEAN MAXIMUM NAIL FORCE - SIMULATIONS 7,8 AND 9 in the simulation process could easily result in fairly large percentage changes of these small values. Mean maximum joist stresses also increased much less with increasing joist E and slip modulus variability for the concentrated loading case. Plywood E variability moved the joist stress mean more for the concentrated loading case. These changes of response mean values caused by concentrated loads with component variability were shown earlier to be quite small in Figs. 4.1-4.7. The trend towards smaller movements of the mean with material variability also is related to the different patterns of response distribution seen in these figures from those displayed for the uniform load in Chapter 3. The cumulative maximum distributions for concentrated loads can be seen to vary about both sides of the values for floors with no variability. In contrast, with the uniform load, maximum response values were almost above the no variation results. The mean maximum nail force values increased a larger percentage with material stiffness variations than did joist deflections or joist tensile stresses.

Figures 4.17 and 4.18 show that joist E and plywood E variabilities both effect the mean maximum joist tensile stress and nail force values more than does the slip modulus variation. The relatively small effect slip modulus variability has on mean maximum nail force is somewhat surprising considering the larger influence found for this variation on the mean maximum deflection for the uniform loading case (Fig. 3.18).

The effective joist E ratio, defined in Section 3.3 as the ratio of critical joist E to the average E of the two adjacent joists, is shown plotted against maximum joist stress in Fig. 4.19. Higher

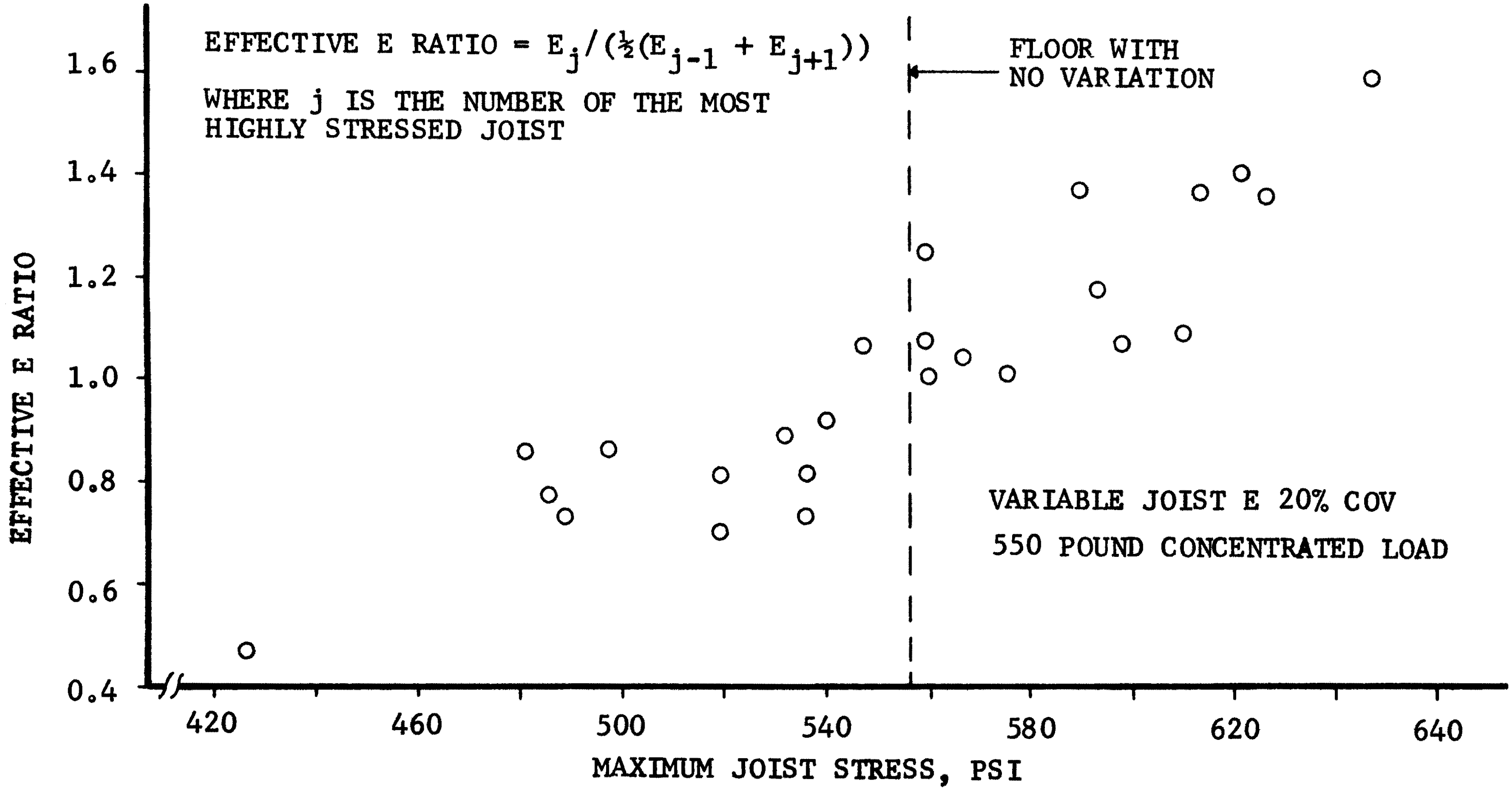


FIGURE 4.19

MAXIMUM JOIST STRESS VS. EFFECTIVE JOIST E RATIO - SIMULATION 7 joist stresses occurred when the adjacent joists were more flexible and thus less able to contribute to the load sharing behavior. The maximum joist stress was next plotted against the E of the most highly stressed joist (Fig. 4.20). The joist stress and its stiffness were found to be well correlated. The stiffer joists again are shown to attract more load and are more highly stressed. These results demonstrate that the maximum joist stress is a function of the relative stiffness of the loaded and adjacent unloaded joists and the relative ability of the latter to participate as load sharing members.

4.3.2 Effects of Plywood Joint Conditions

The floors of Simulations 2 and 10 were identically specified except for the use of tongue and groove plywood joints in Simulation 2 and butted plywood joints in Simulation 10. The response of these two floors, both loaded with a uniform load of 40 psf, are compared in Figs. 4.21, 4.22 and 4.23. As expected, the butted plywood system displayed larger deflections and joist stresses. However nail forces were consistently higher for the tongue and groove plywood floor system (Fig. 4.23). These higher nail forces with stiffer tongue and groove plywood joints can be explained by the increased structural interaction and the resulting higher interlayer shear forces. The mean values for the maximum floor deflection and tensile stress response (at 50 percent frequency) increased 19 percent and 10 percent respectively when butted joints were substituted for tongue and groove joints. Nail forces dropped approximately 22 percent.

Figures 4.24 and 4.25 show the effect of critical joist E and the effective joist E ratio on the maximum tensile stress of that critical joist for the butted plywood floor system. A comparison of

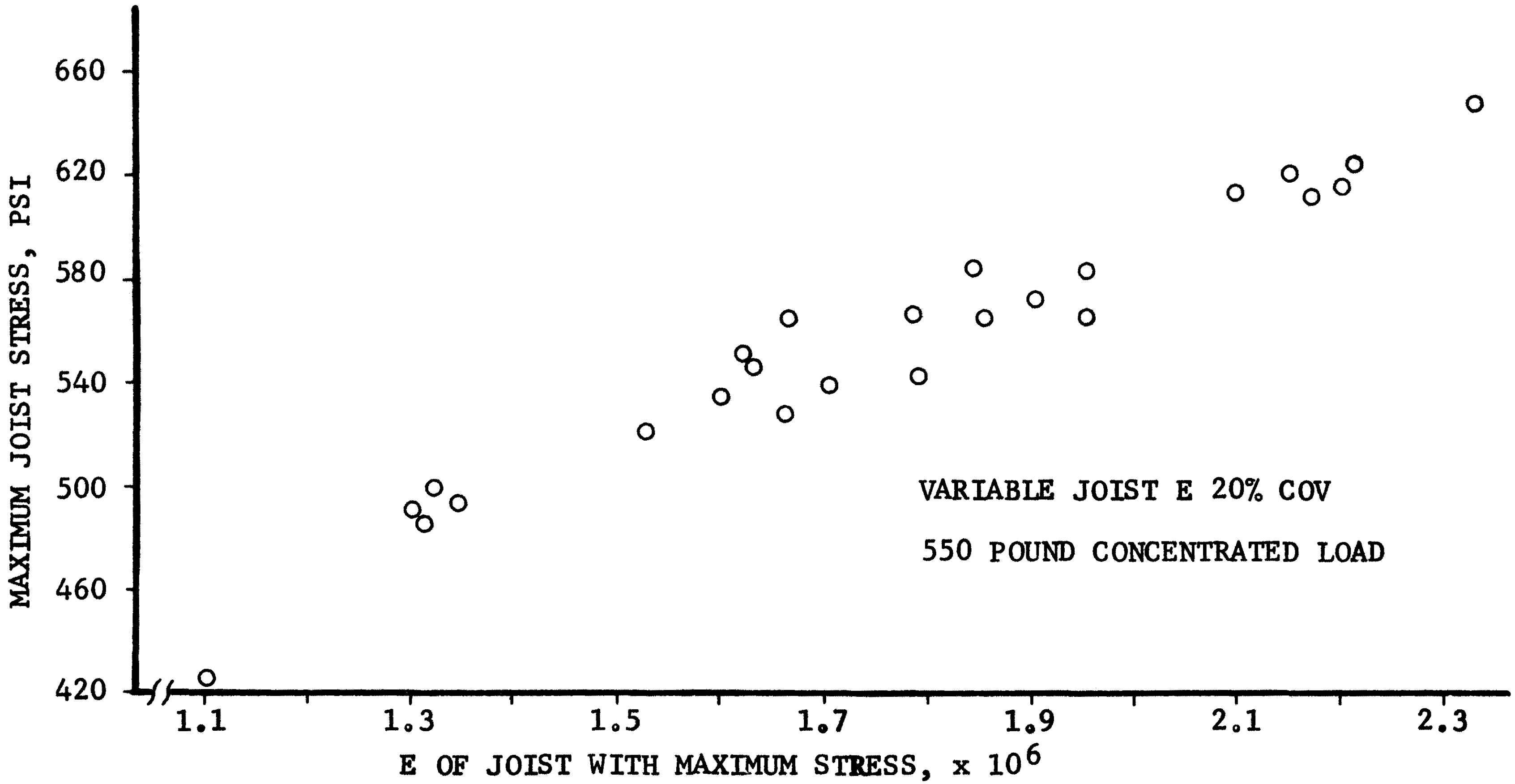


FIGURE 4.20

E OF JOIST WITH MAXIMUM STRESS VS. MAXIMUM JOIST STRESS - SIMULATION 7

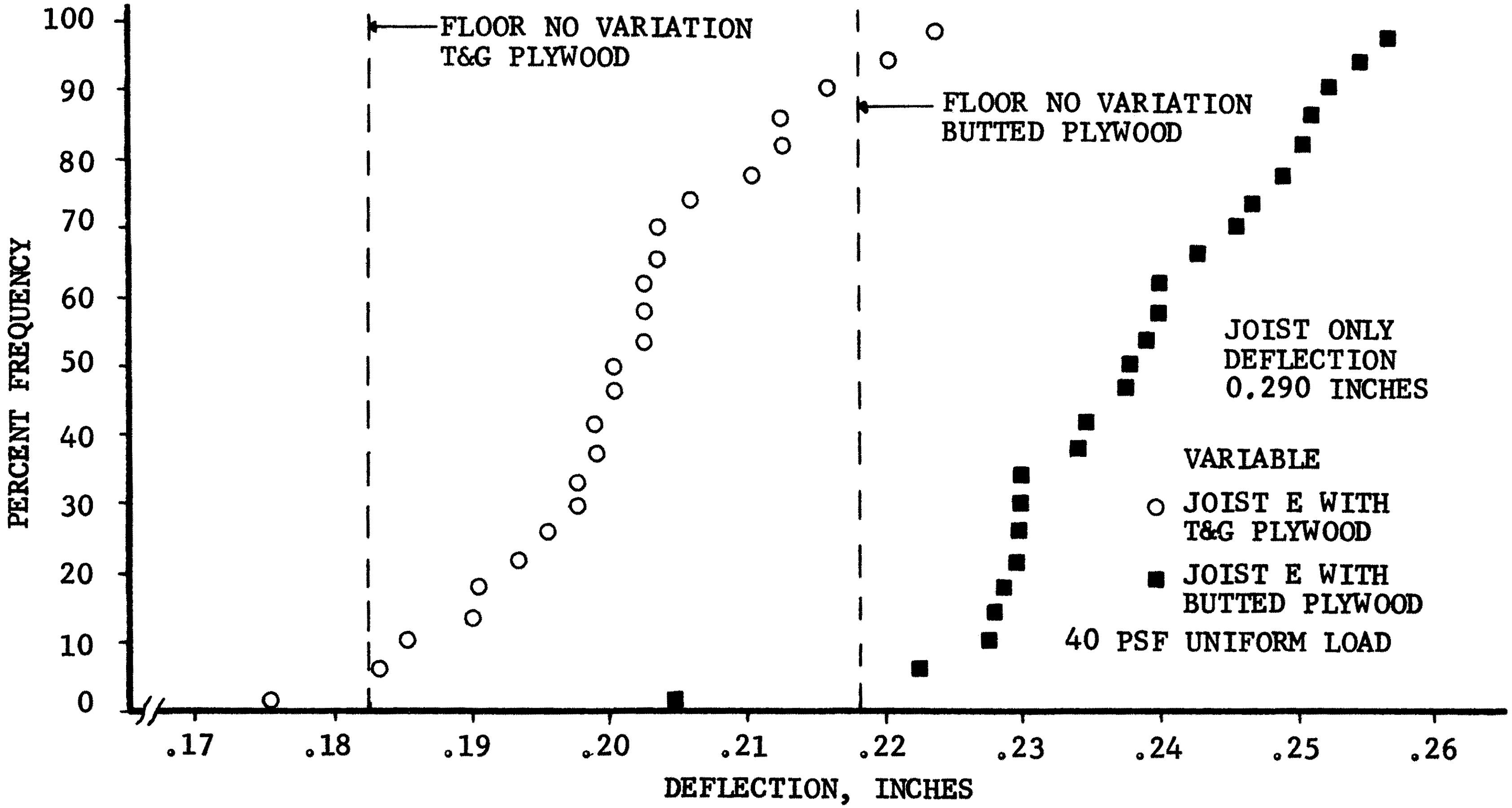


FIGURE 4.21

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATIONS 2 AND 10

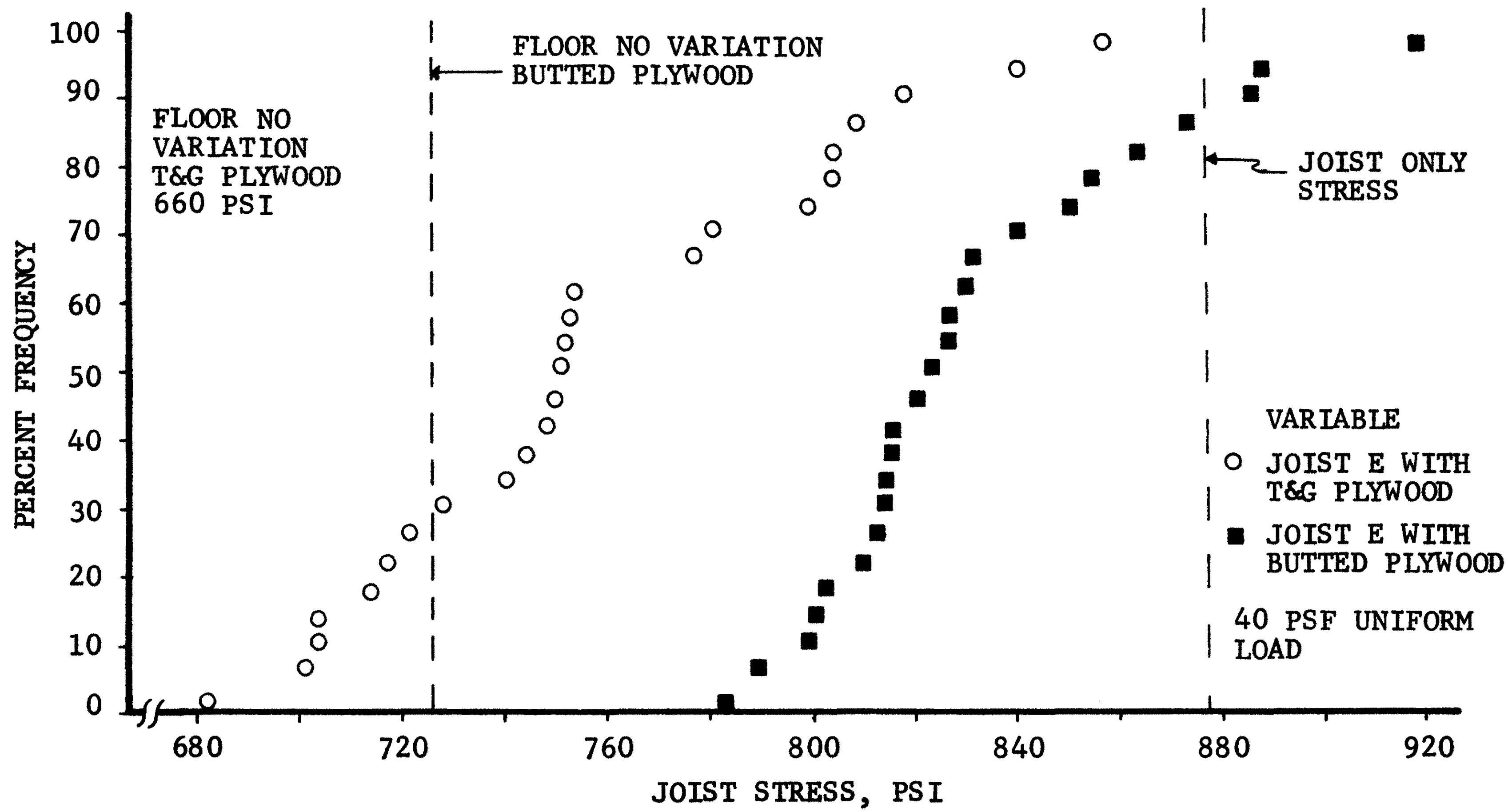


FIGURE 4.22

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATIONS 2 AND 10

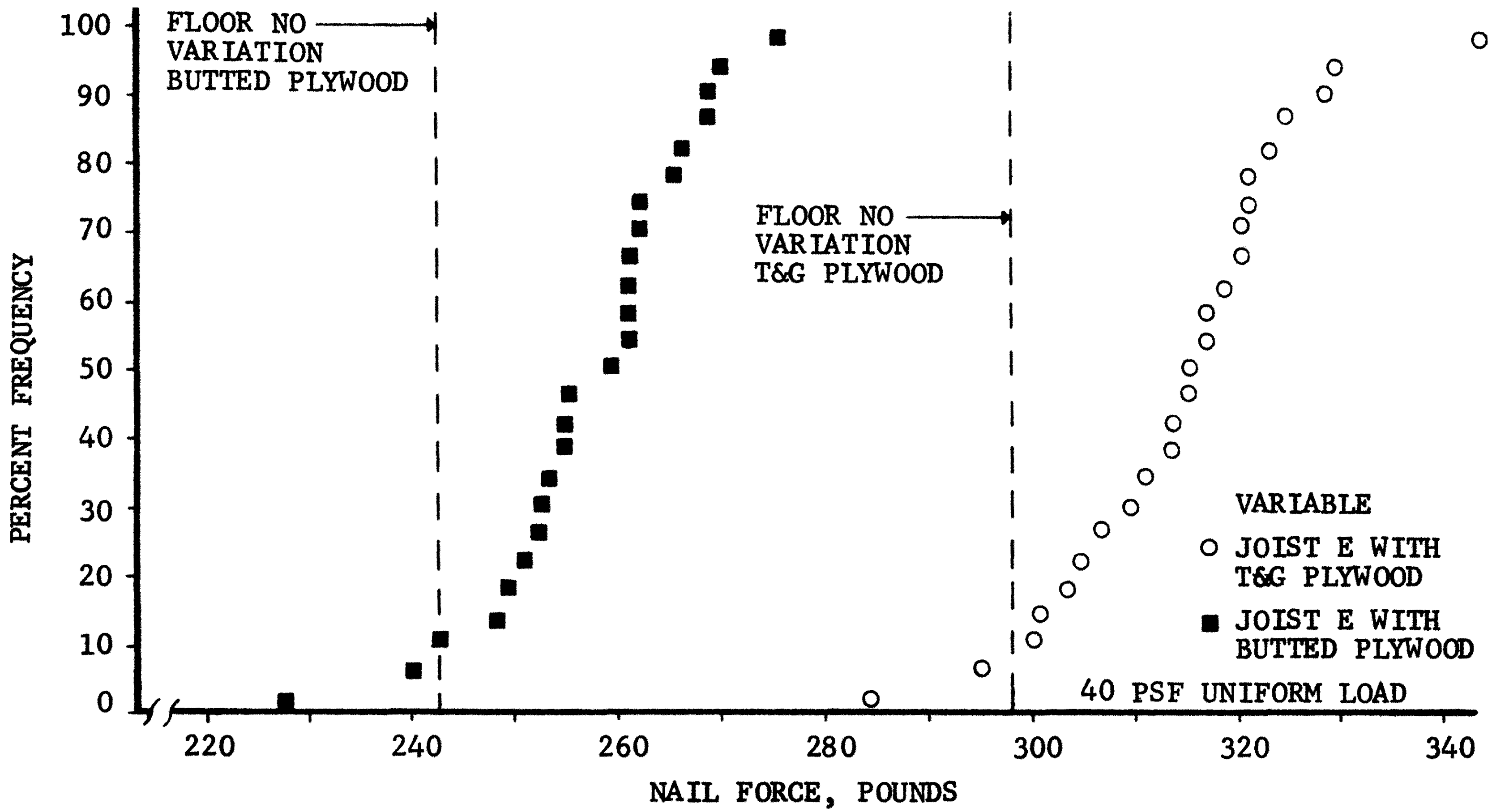


FIGURE 4.23
CUMULATIVE MAXIMUM NAIL FORCE DISTRIBUTION - SIMULATIONS 2 AND 10

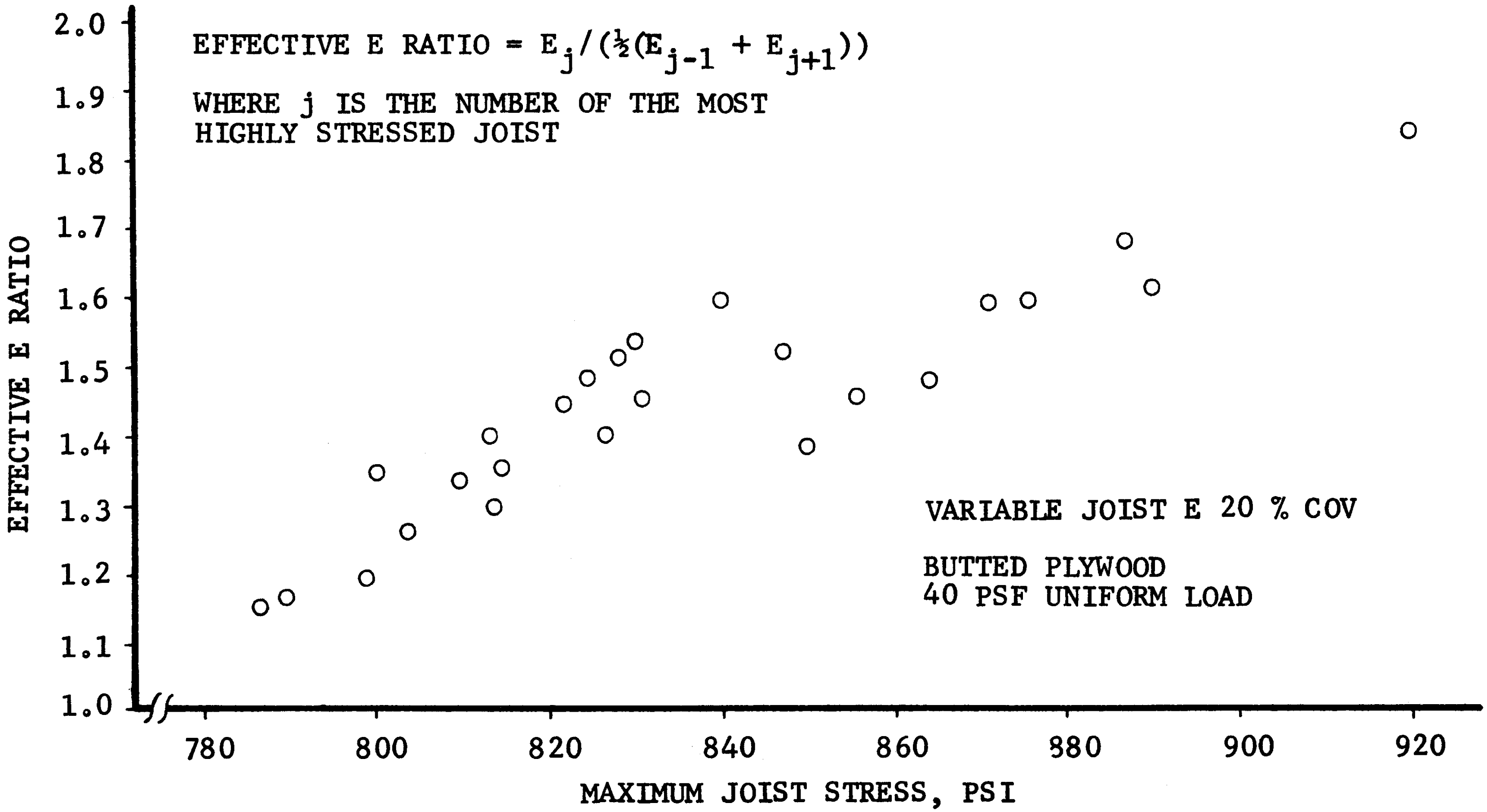


FIGURE 4.24

MAXIMUM JOIST STRESS VS. EFFECTIVE JOIST E RATIO - SIMULATION 10

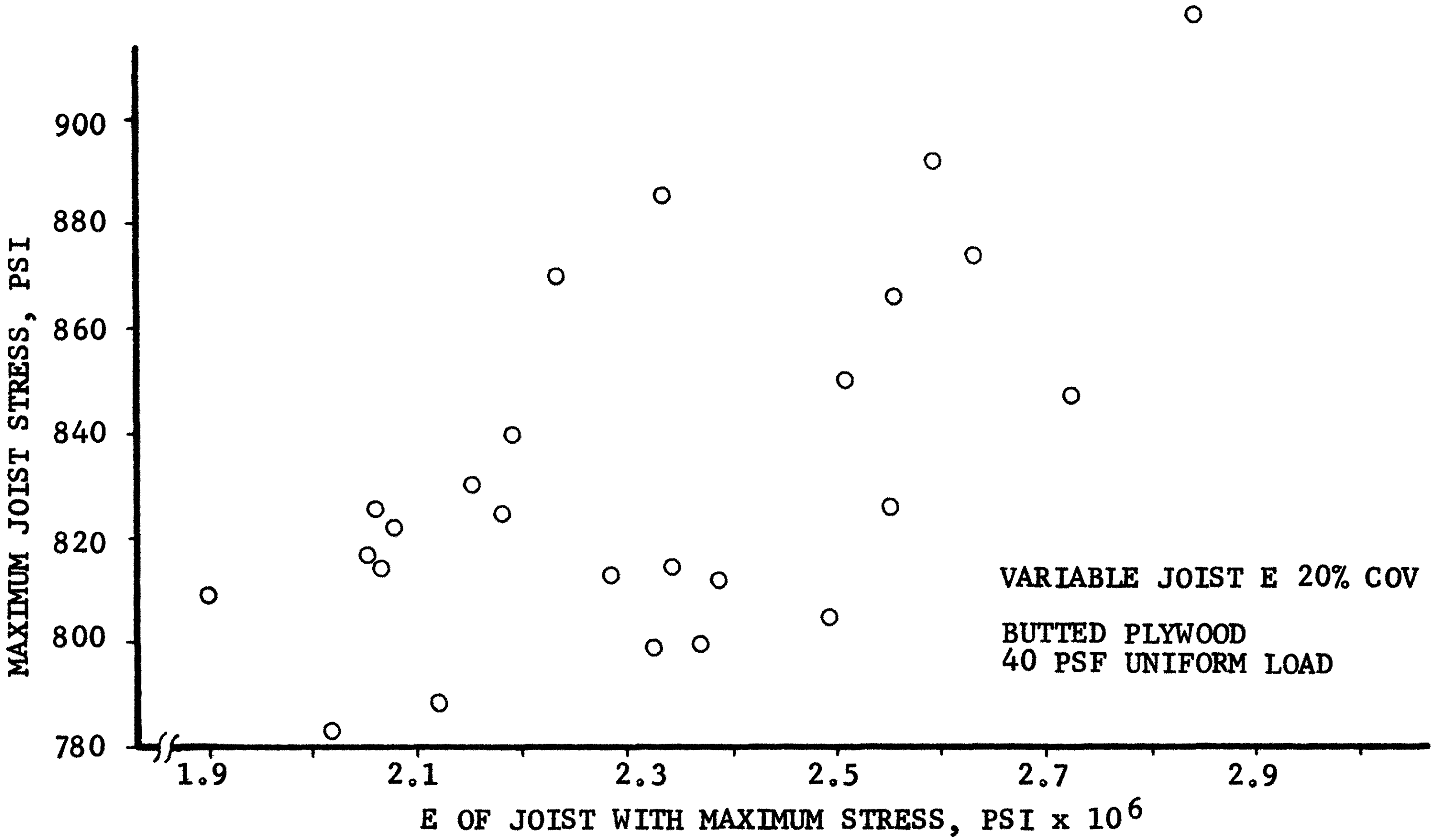


FIGURE 4.25
E OF JOIST WITH MAXIMUM STRESS VS. MAXIMUM JOIST STRESS - SIMULATION 10

these two plots with Figs. 3.19 and 3.20, plots for the same floor except with tongue and groove plywood joints, shows that the butted system has more scatter when maximum joist stress is shown versus the E of this joist.

4.3.3 Influence of Plywood Thickness on Maximum Joist Deflections and Tensile Stresses

Use of thinner sheathing layers results in increases of both the joist stresses and deflections, as would be expected. Figure 4.26 shows a relationship between plywood thickness and the mean maximum joist deflection. The values plotted were obtained from deflection results of Simulations 6 and 11 which, except for the plywood thickness, are identical in geometry and material variability. The value for zero plywood thickness was obtained from joist-only deflection results from these same two simulations. The dashed line is a linear approximation that matches the nonlinear relationship to within plus or minus 0.025 inches for the range shown.

Figure 4.27 shows a relationship between plywood thickness and mean maximum joist tensile stress. The data plotted is from the same sources as used for Fig. 4.26. The dashed line is a linear relationship that approximates the nonlinear form to within plus or minus 10 psi.

The various floor configurations and loading cases presented in this and other sections of this chapter were chosen to study several of the common and considered important modifications of the basic floor investigated in Chapter III which exist in actual floors. Obviously, many other combinations of changes in component dimensions, loading patterns, material properties and/or floor size could be similarly

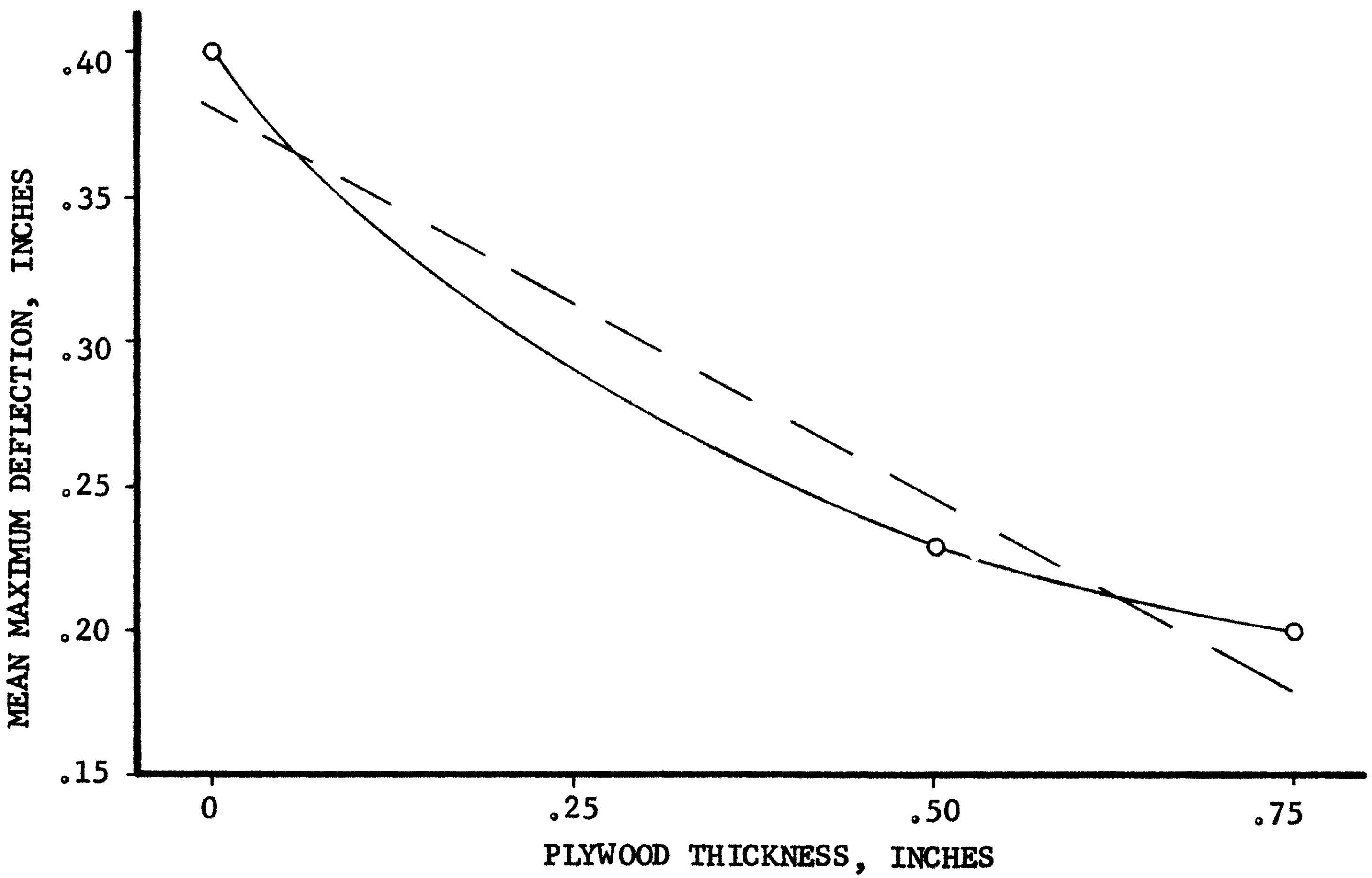


FIGURE 4.26

PLYWOOD THICKNESS VS. MEAN MAXIMUM DEFLECTION - SIMULATIONS 6 AND 11

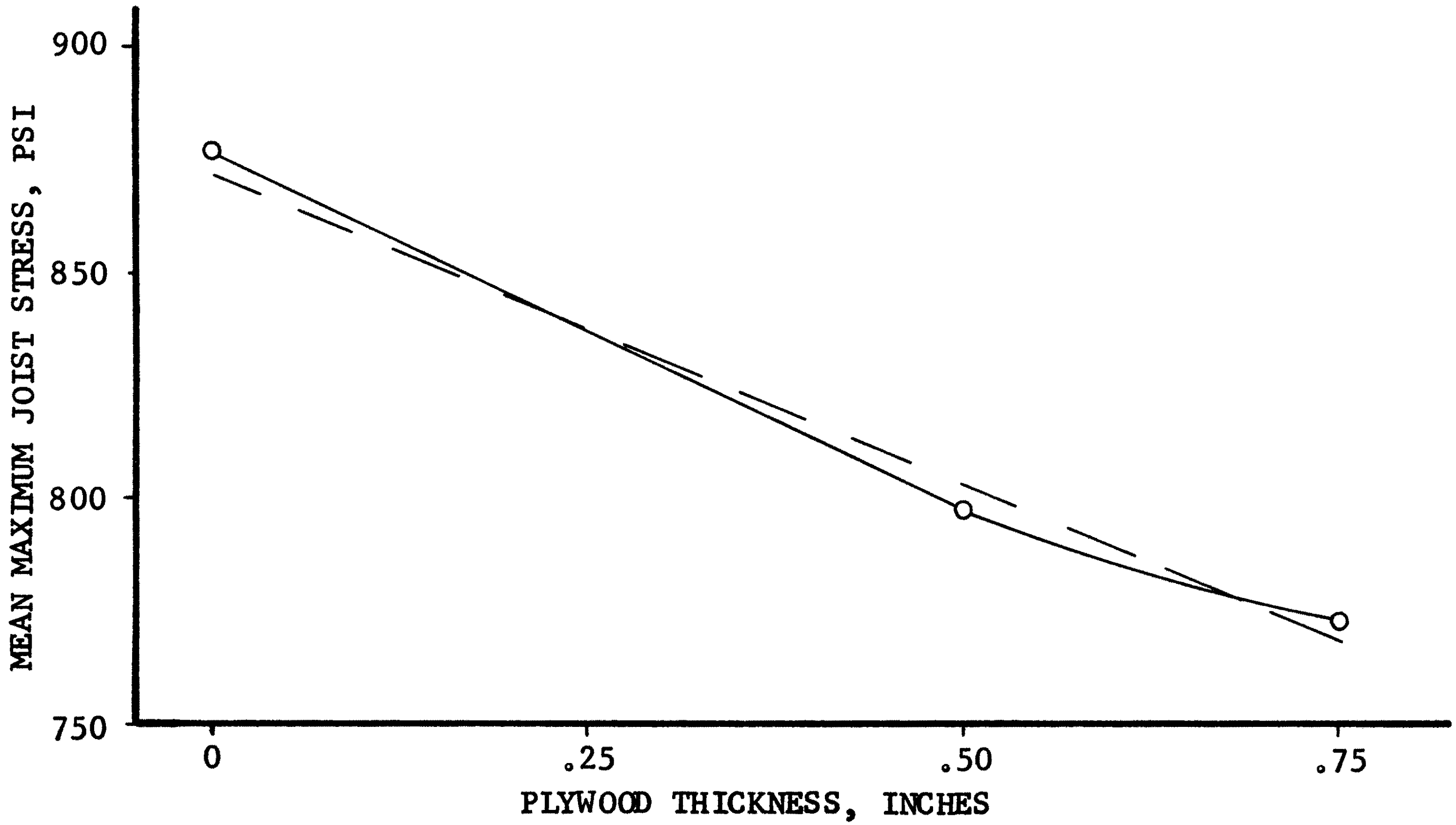


FIGURE 4.27
PLYWOOD THICKNESS VS. MEAN MAXIMUM JOIST STRESS - SIMULATIONS 6 AND 11

studied. Although floor descriptions other than those present here will result in different numerical relationships between input property variations and response characteristics, consideration of floors similar to those herein reported would be expected to result in similar relationships.

Chapter V

SIMULATIONS OF DESIGN CODE MINIMUM FLOORS

5.1 Properties of the Minimum Floors

A minimum floor will be defined for this study as a floor including the minimum combination of joist size, plywood thickness and properties allowed by the specifications of one or more recognized specification producing agencies, including the Uniform Building Code (24), the Building Officials Code Administrators (25), and the Federal Housing Administration (26) for floor systems constructed with joists of 1.6×10^6 psi mean modulus of elasticity (E) and spaced 16 inches on center. The floors investigated consisted of either two or three layers. The bottom two layers always consisted of the joists and plywood sheathing in the arrangement shown in Fig. 3.1. The third layer when used was either a continuous layer of hardwood flooring or butted sheets of 4 ft by 8 ft particle board orientated with the 8 ft dimension perpendicular to the joists. Gaps in the layer of particle board were staggered one-half of the 4 ft by 8 ft sheet dimension from the gaps in the plywood layer below. Thus, the third layer had a gap along the centerline locations of the joists.

The material properties used for each simulation are summarized in Tables 5.1 and 5.2. Material property cutoff values used in limiting assigned components stiffnesses were set at plus or minus two standard deviations from the mean value. Thus, about five percent of the component stiffnesses, mostly the highest values due to the skewness of the distribution, were expected to be controlled by either the upper or lower cutoff value.

TABLE 5.1 Two-Layered Minimum Floor Systems

Simulation Number	Mean Joist E PSI x 10^{+6}	COV Joist E Percent	Mean Plywood E*, PSI x 10^{+6}	COV Plywood E, Percent	Plywood Thickness Inches	Plywood Connection Type	Mean Slip Modulus lbs/in.	COV Slip Modulus Percent
12	1.600	20.0	0.0737 ⊥ 0.7620 ⊥⊥	0	5/8	T&G	18,000	0
13	1.600	20.0	0.0737 ⊥ 0.7620 ⊥⊥	20.0	5/8	T&G	18,000	40.0
14	1.600	20.0	0.101 ⊥ 1.310 ⊥⊥	20.0	1/2	T&G	30,000	60.0
15	1.600	0	0.394 ⊥ 1.385 ⊥⊥	11 A.M. 13 W.M.	19/32	T&G	22,700	0
16	1.600	9 A.M. 18 W.M.	0.394 ⊥ 1.385 ⊥⊥	11 A.M. 13 W.M.	19/32	T&G	22,700	0
17	1.600	9 A.M. 18 W.M.	0.394 ⊥ 1.385 ⊥⊥	11 A.M. 13 W.M.	19/32	T&G	22,700	60.0
18	1.600	18 W.M.	0.394 ⊥ 1.385 ⊥⊥	0	19/32	T&G	22,700	0
19	1.600	9 A.M.	0.394 ⊥ 1.385 ⊥⊥	0	19/32	T&G	22,700	0
20	1.600	9 A.M. 18 W.M.	0.394 ⊥ 1.385 ⊥⊥	0	19/32	T&G	22,700	0

A.M. = Among Mill Variation
W.M. = Within Mill Variation
T&G = Tongue and Groove Plywood Connection
COV = Coefficient of Variation
* = Using Gross Untransformed Section
⊥ = Perpendicular E Value in Flexure
⊥⊥ = Parallel E Value in Flexure

1/2 and 5/8-in. plywood: Unsanded panels with all plies from the same species group, identification index = 32/16 for both. Species group 1 for 1/2-in. thickness, group 3 for 5/8-in. thickness (See PDS Spec., Ref. 20).
Property values for 19/32-in. plywood supplied by National Forest Products Association (NFPA).

E of joint elements = 10000 psi for joints in both directions and for both axial load and bending
Length of joint elements = 0.10 in.

TABLE 5.2 Three-Layered Minimum Floor Systems

Simulation Number	Mean Joist E PSI x 10^{+6}	COV Joist E Percent	Mean Plywood E*, PSI x 10^{+6}	COV Plywood E, Percent	Plywood Thickness Inches	Plywood Connection Type	Mean Third Layer E 10^6 psi Units	COV Third Layer Percent	Third Layer Thickness Inches	Mean Slip Modulus lbs/in. (Between Joist and Plywood)	COV Slip Modulus Percent	Slip Modulus lbs/in. (Between Plywood and Third Layer)
21	1.600	20.0	0.0737 $\perp$ 0.7620 $\parallel$	20.0	5/8	T&G	0.250	0	1/2	35,000	40.0	3,000
22	1.600	0	0.0737 $\perp$ 0.7620 $\parallel$	0	5/8	T&G	0.250	40.0	1/2	35,000	0	3,000
23	1.600	9 A.M. 18 W.M.	0.315 $\perp$ 1.440 $\parallel$	11 A.M. 13 W.M.	1/2	BUTTED	0.080 $\perp$ 1.160 $\parallel$	0	25/32	35,000	0	16,200
24	1.600	9 A.M. 18 W.M.	0.315 $\perp$ 1.440 $\parallel$	11 A.M. 13 W.M.	1/2	BUTTED	1.080 $\perp$ 1.160 $\parallel$	0	25/32	35,000	0	16,200

A.M. = Among Mill Variation
W.M. = Within Mill Variation
T&G = Tongue and Groove Plywood Connection
COV = Coefficient of Variation
* = Using Gross Untransformed Section
$\perp$ = Perpendicular E Value in Flexure
$\parallel$ = Parallel E Value in Flexure

Third layer E$\parallel$ for Simulations 23 and 24 of 1.60 x 10^6 psi were first chosen and is more typical for oak. 1.16 x 10^6 value used by error and was discovered during final report preparation.

E of joint elements (same for both axial load and bending)

Plywood layer, for joints both parallel and perpendicular to joists
Simulations 21, 22 10000 psi
Simulations 23, 24 500 psi

Particle board third layer (Simulations 21, 22)
Joints perpendicular to joists 500 psi
Joints parallel to joists none included

5.2.1 Simulations of Floors with 5/8 inch Thick Plywood

Two simulations were conducted using floors with one sheathing layer consisting of 5/8 inch plywood with a gross untransformed E values of 73,700 psi perpendicular and 762,000 psi parallel to the face ply. These two floors, identified as Simulations 12 and 13 in Table 5.1, are basically the same except that floor 13 had the plywood E and nail slip modulus values varied (20 and 40 percent respectively) in addition to having the 20 percent joist E COV also specified for Simulation 13 (see Table 5.1).

The cumulative distribution of the maximum joist deflection within each floor and the maximum joist tensile stress within each floor for Simulations 12 and 13 are shown in Figs. 5.1 and 5.2, respectively. The two simulations of the 5/8 inch plywood floor system, with and without plywood and connector stiffnesses varied, were conducted to demonstrate that consideration of joist E approximates the response resulting from the simultaneous variation of joist E, plywood E and slip modulus. The mean response values and the listed COV for the responses, along with the values for other simulations are in Table 6.1 of Chapter VI. The mean maximum joist deflection increased only slightly (from 0.278 in. to 0.286 in.) when plywood and connector stiffness variations were added to the floor with variable joist E values. The deflection response COV increased from 5.4 percent to 6.6 percent.

Figure 5.1 shows that all of the maximum floor deflections for both simulations are below the joist-only deflection computed with the mean E. However, the maximum joist tensile stress distributions (Fig. 5.2) show that some maximum floor joist stresses are higher than

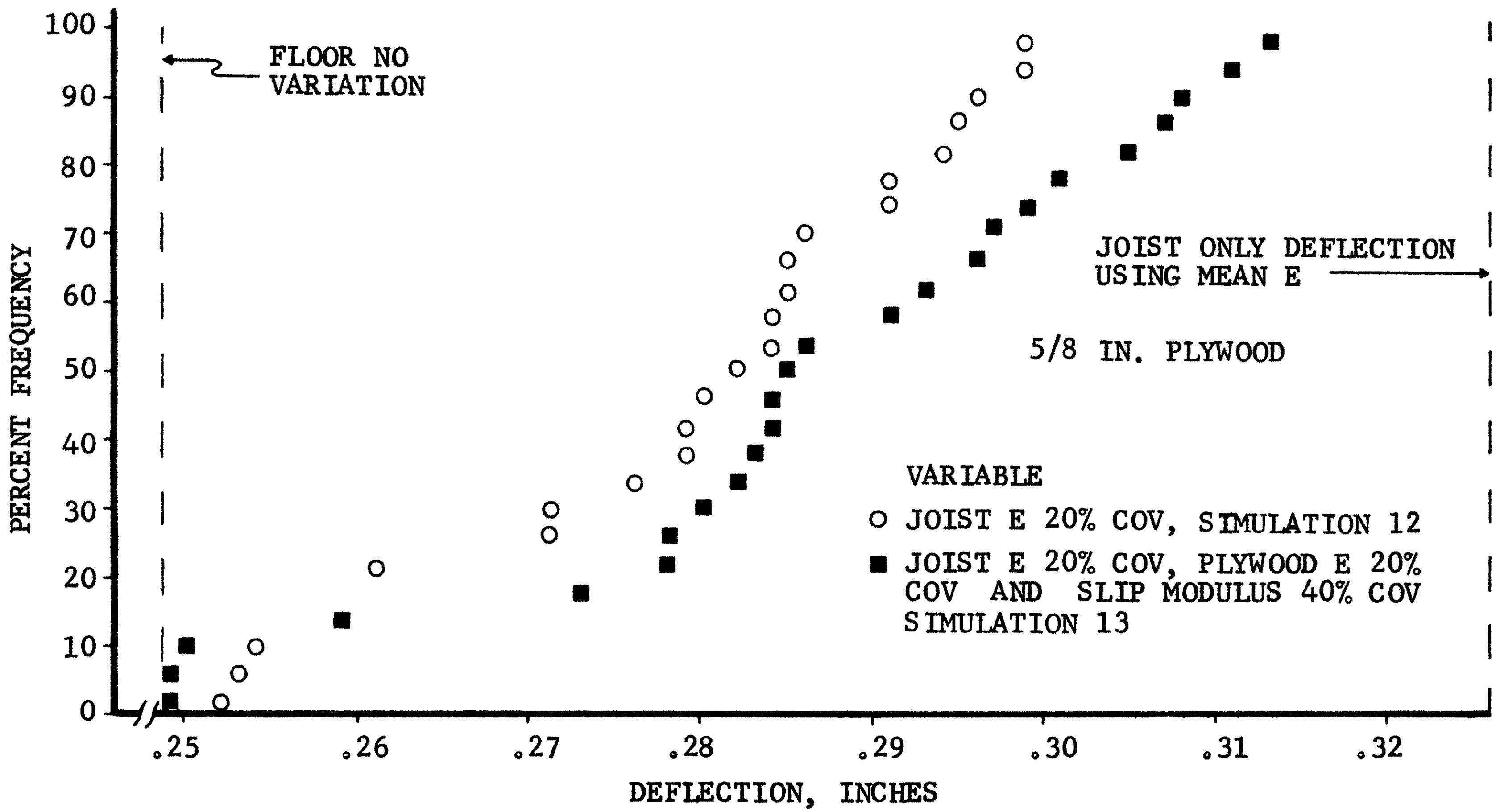


FIGURE 5.1
CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATIONS 12 AND 13

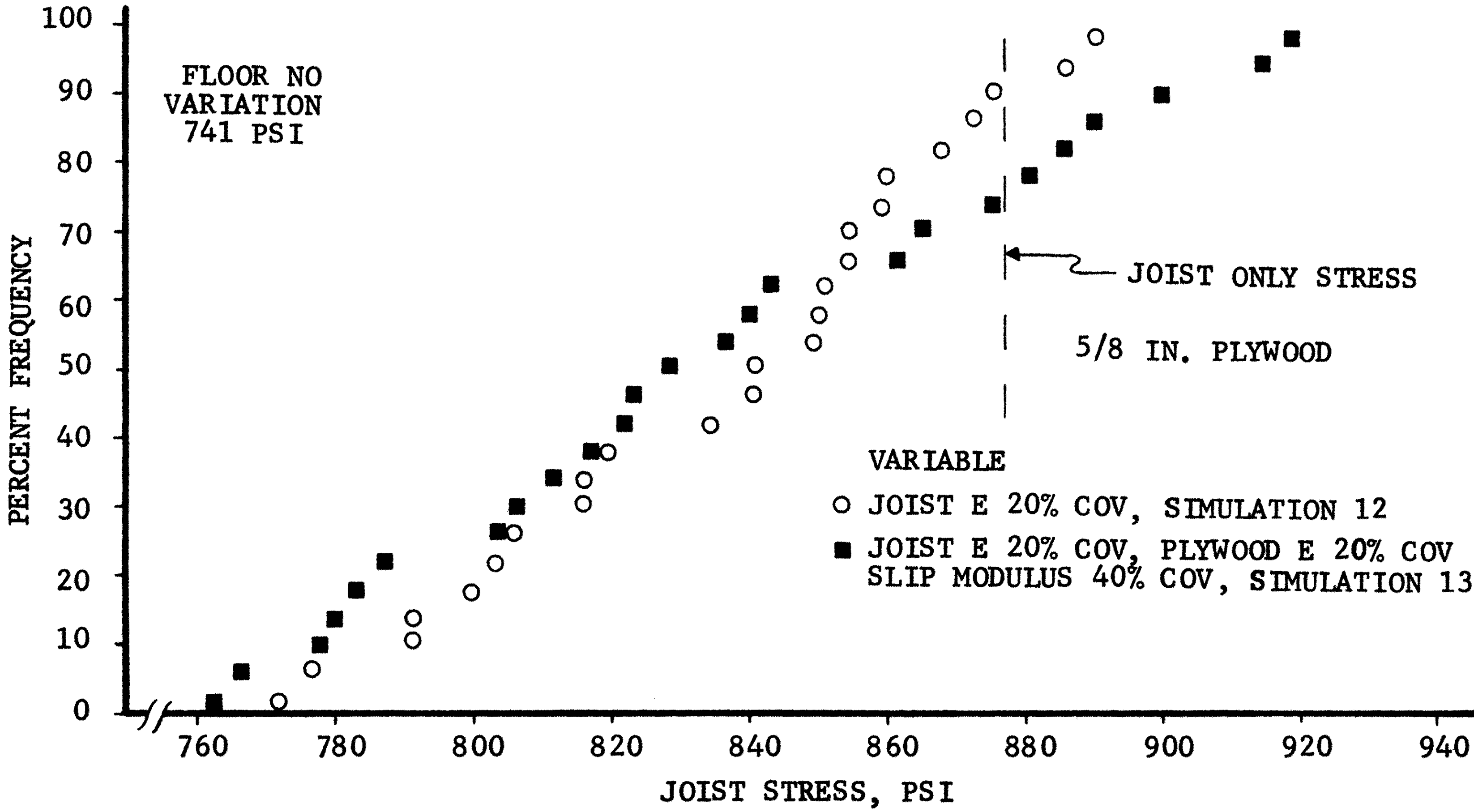


FIGURE 5.2

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATIONS 12 AND 13

given by a joist-only calculation. Just as was the case for floor simulations reported in Chapter III (see Fig. 3.3), these highly stressed joists were also noticably stiffer than the average joist. The average of the E values for the eight joists having stresses above the joist-only value was 2,040,000 psi, 128 percent of the mean joist stiffness. The mean of the maximum tensile joist stresses were essentially the same for Simulations 12 and 13 (835 psi for Simulation 12 versus 836 psi for Simulation 13).

Figure 5.3 shows the considerable reduction of deflection which exists when the floor with variable component stiffness is analyzed as an interacting system of components instead of a number of isolated joists.

5.2.2 Response of a Floor System with 1/2-inch Plywood

A 1/2 in. thick plywood floor with properties given in Table 5.1 as Simulation 14 is also a minimum floor. Figures 5.4 and 5.5 show the response of this 1/2 in. plywood floor system. The cumulative maximum (per floor) joist deflection distribution (Fig. 5.4) shows that even with this small plywood thickness, all joist deflections of all of these minimum floors are below the joist-only deflection computed with the mean E. The cumulative maximum (per floor) joist tensile stress distribution (Fig. 5.5) shows that one floor of the twenty-five included in this simulation had a maximum joist stress exceeding that given by the joist-only flexural stress. This highest stressed joist had an E value of 2.26×10^6 psi and was adjacent to joists with 1,190,000 psi and 1,750,000 psi E values.

A comparison of the response of floors 13 (Figs. 5.1 and 5.2) with that of Simulation 14 (Figs. 5.4 and 5.5) shows that the thinner but

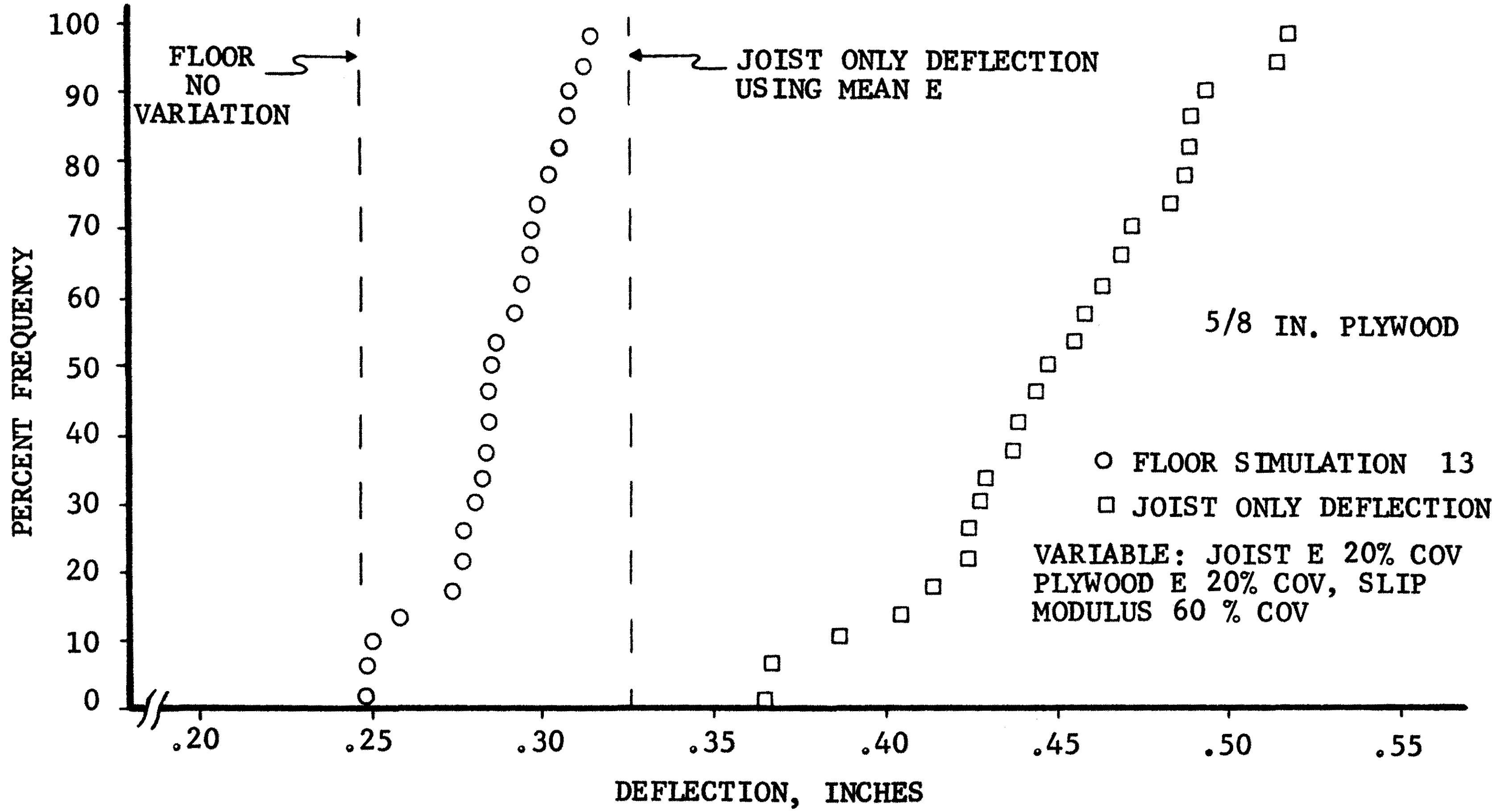


FIGURE 5.3

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 13

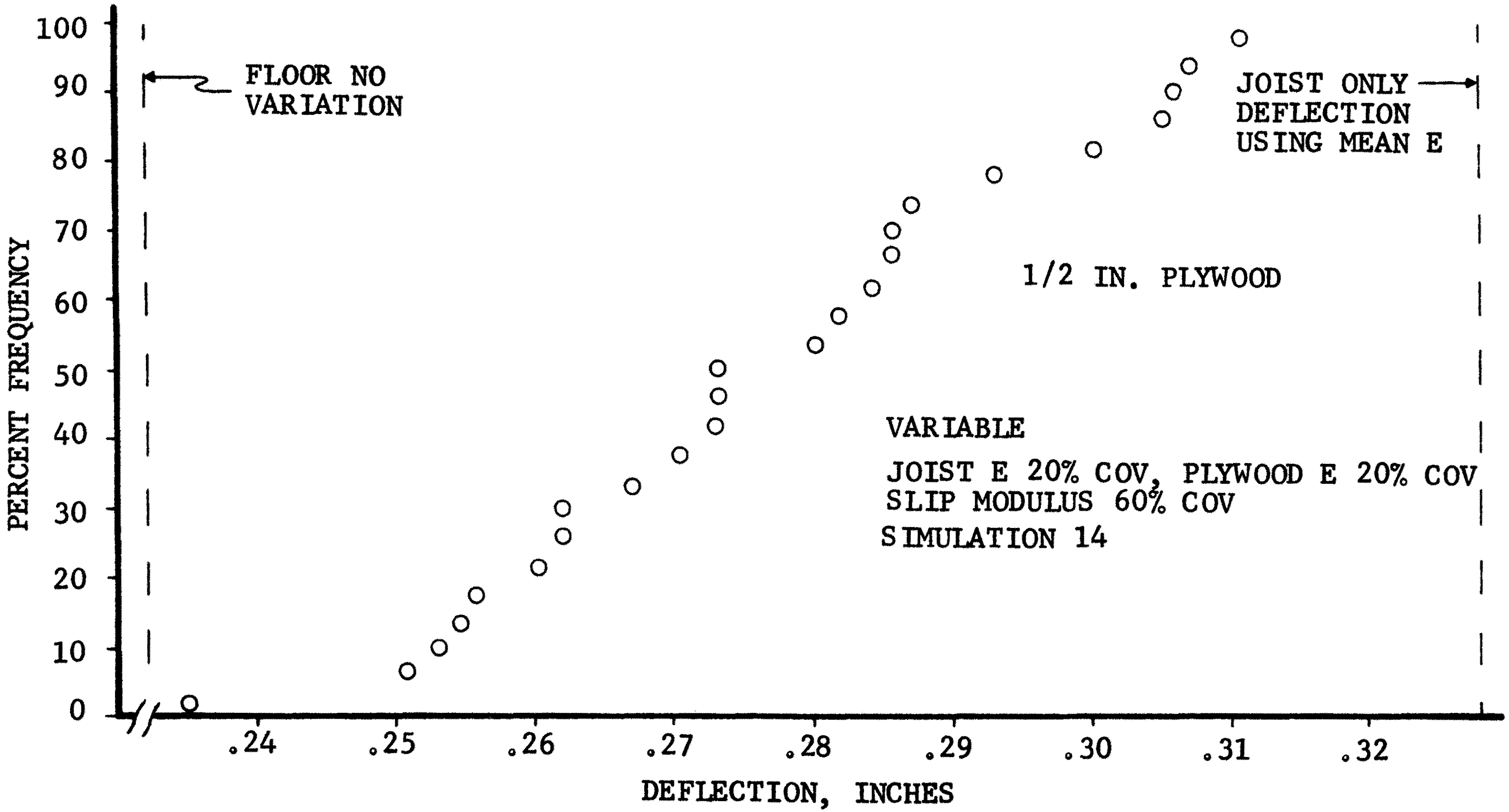


FIGURE 5.4

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 14

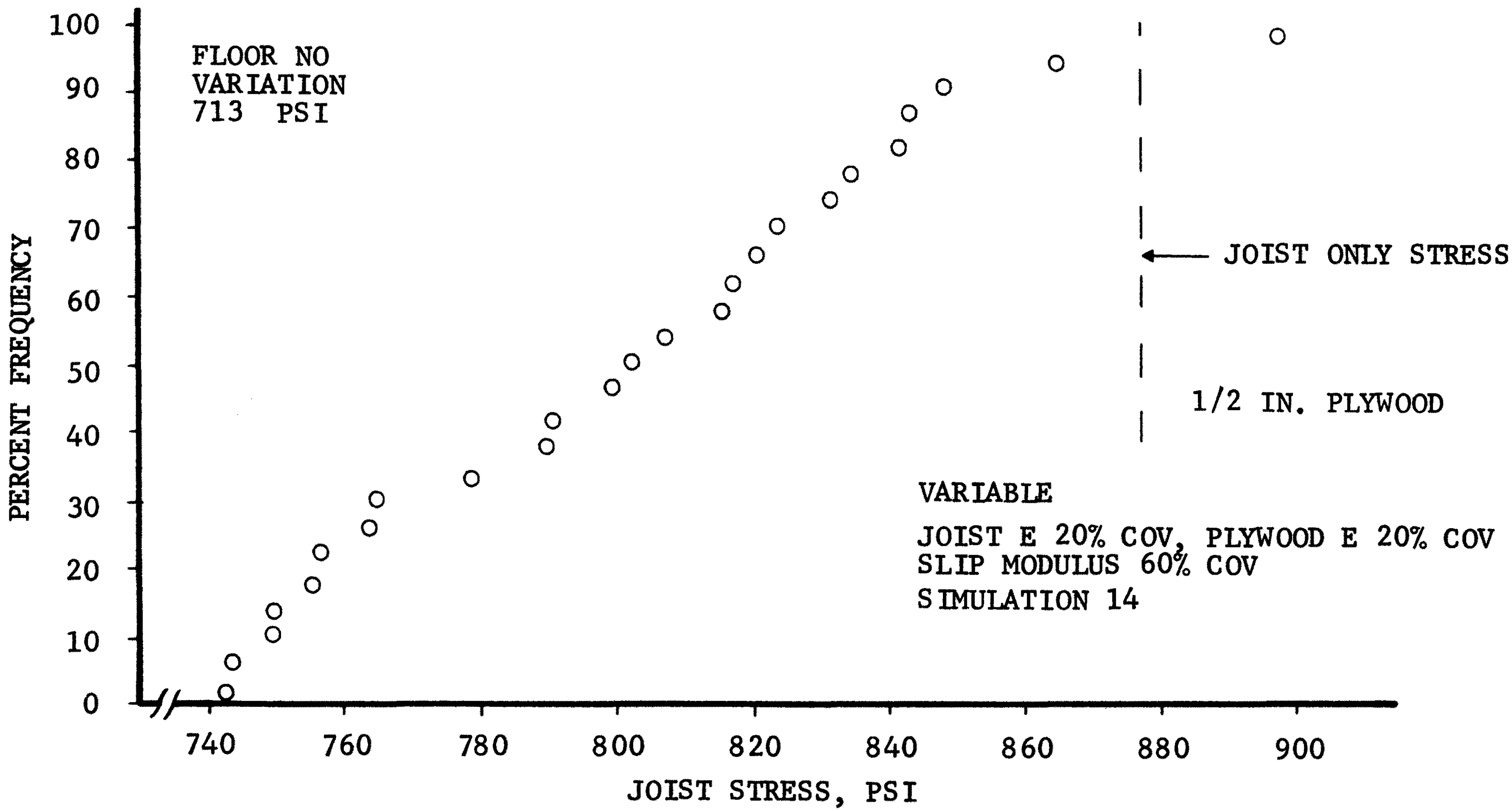


FIGURE 5.5
CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 14

stiffer plywood sheathing was more effective in reducing both maximum joist deflection (from a mean of 0.282 inch to 0.273 inch) and joist stresses (827 psi to 802 psi). The higher connector slip modulus also contributed to this improved performance for the thinner but stiffer sheathing.

Figure 5.6 displays the large differences in predicted deflection of the floor with component variation when treated as an integrated floor system versus that given by the joist-only assumption.

5.2.3 Response of Floors with 19/32 inch Plywood and Among and Within Mill Variabilities

The material properties used for simulation numbers 15, 16 and 17 were supplied by the National Forest Products Association (N.F.P.A.). Both a between mill and a within mill distribution sampling procedure were used in these simulations. Among mill variations could be expected to arise from the differences in timber properties used by the individual mills and from some individual mill characteristics and practices. Timber properties, including density and strength, vary with geographical location and climate. Within mill variations result from the variation of density, defect size and distribution, grading, and other variables within the population of timber providing the mill.

All the joists and sheathing of a floor was assumed to come from one mill. When the among mill variations were considered (Tables 5.1 and 5.2), the mean property stiffness for the individual floors in the simulation were randomly selected from the specified among mill variation. When within mill variations were included, the stiffness of the individual components were selected from a population with the specified mean for the floor (as set by the sampling of among mill variation) and with the within-mill variation.

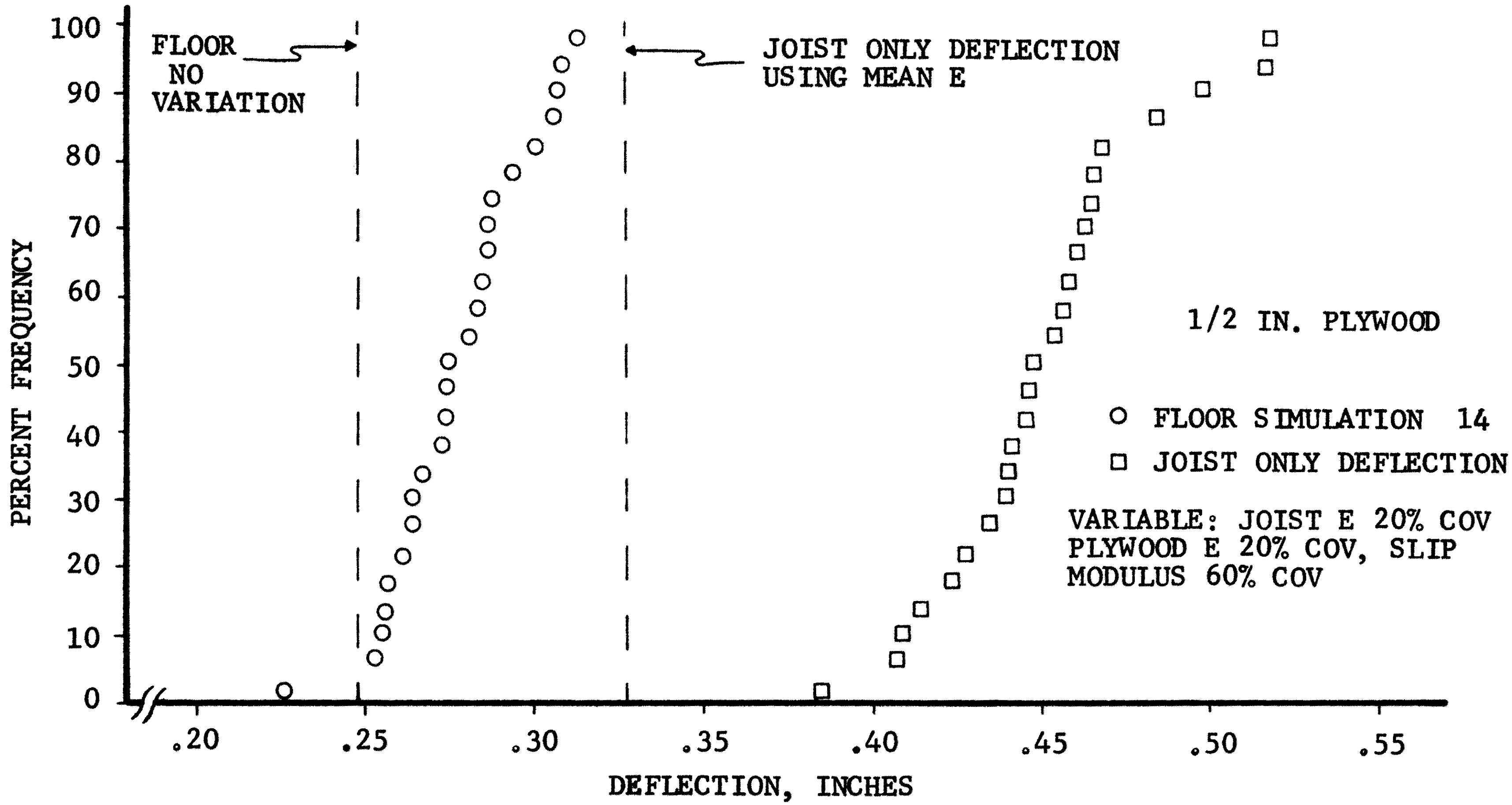


FIGURE 5.6

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 14

Six simulations were included in this series. For Simulation 15, only plywood stiffness was varied and both within and among mill variations were used. Simulation 20 included both types of variation for the joists. Simulation 16 combined both sources of variability for both the plywood sheathing and the joists. Simulation 17 added variability of the connector stiffness (COV of 60 percent) to the parameters varied in Simulation 16. The following coefficients of variation were used when the component listed was assigned variable stiffnesses: joist within mill - 18 percent, joist among mill - 9 percent, plywood within mill - 13 percent and plywood among mill - 11 percent. In addition, Simulations 18 and 19, which contained consideration of the joist within mill variability only and the joist among mill variability only, respectively, were added to help evaluate the relative influence of these two sources of variability.

Figures 5.7 and 5.8 show the cumulative distributions of maximum (per floor) joist deflections and joist tensile stresses for Simulations 15, 16 and 17. The plywood E variability alone results in small variations of both maximum joist deflection and maximum joist tensile stress variation, as was previously reported in Section 3.3. The effect of the slip modulus variability (60 percent COV) on deflection can be approximated by comparing the response of Simulations 16 and 17 of Fig. 5.7. The large influence seen when the joist E variability is added, as well as the results of Simulation 20, discussed later, demonstrates that the joist E variability is by a large margin the major contributor to the response variation, as would be expected considering the results reported in Section 3.3. The joist only E variability (Simulation 20) increases the mean value and variation of

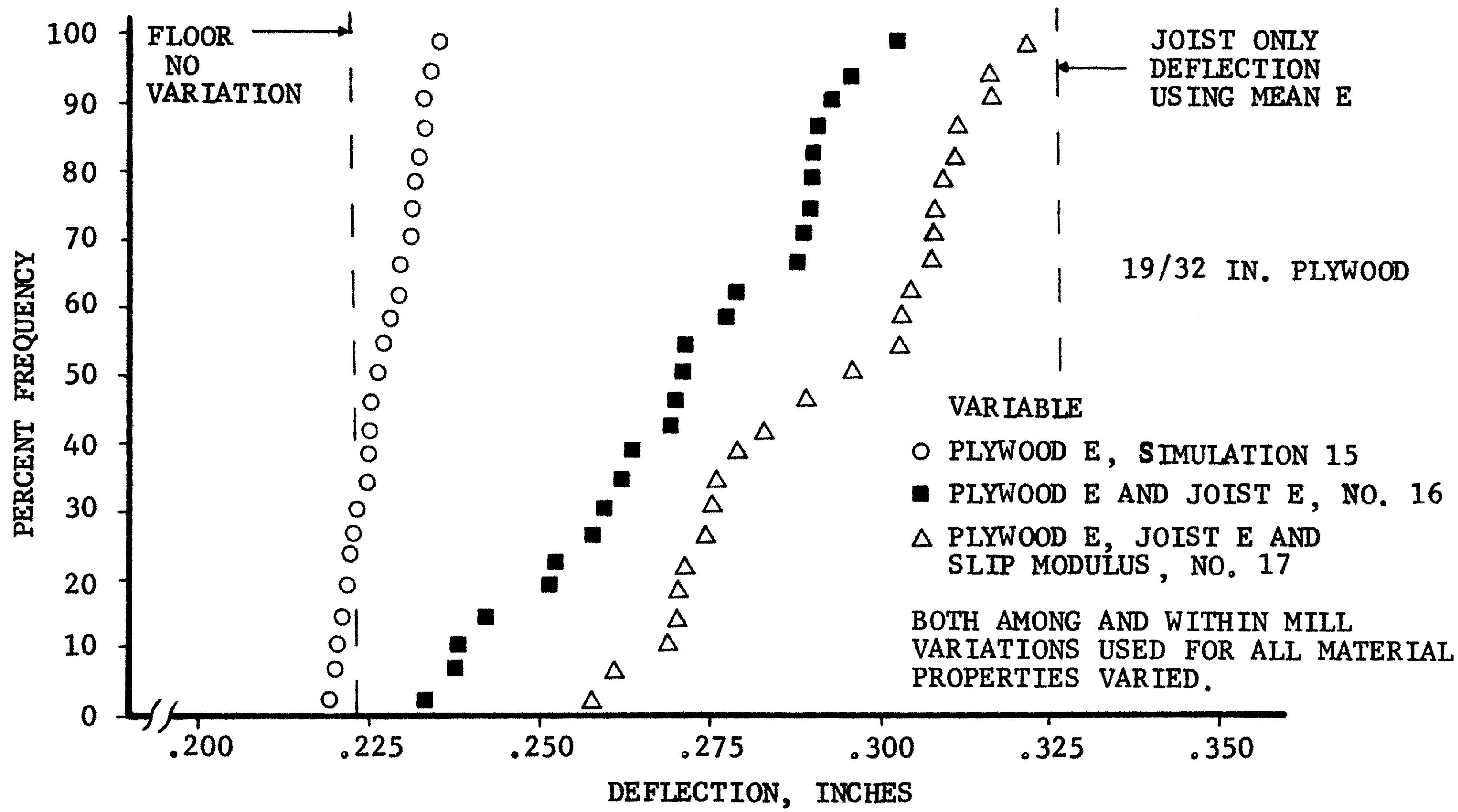


FIGURE 5.7

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATIONS 15, 16 AND 17

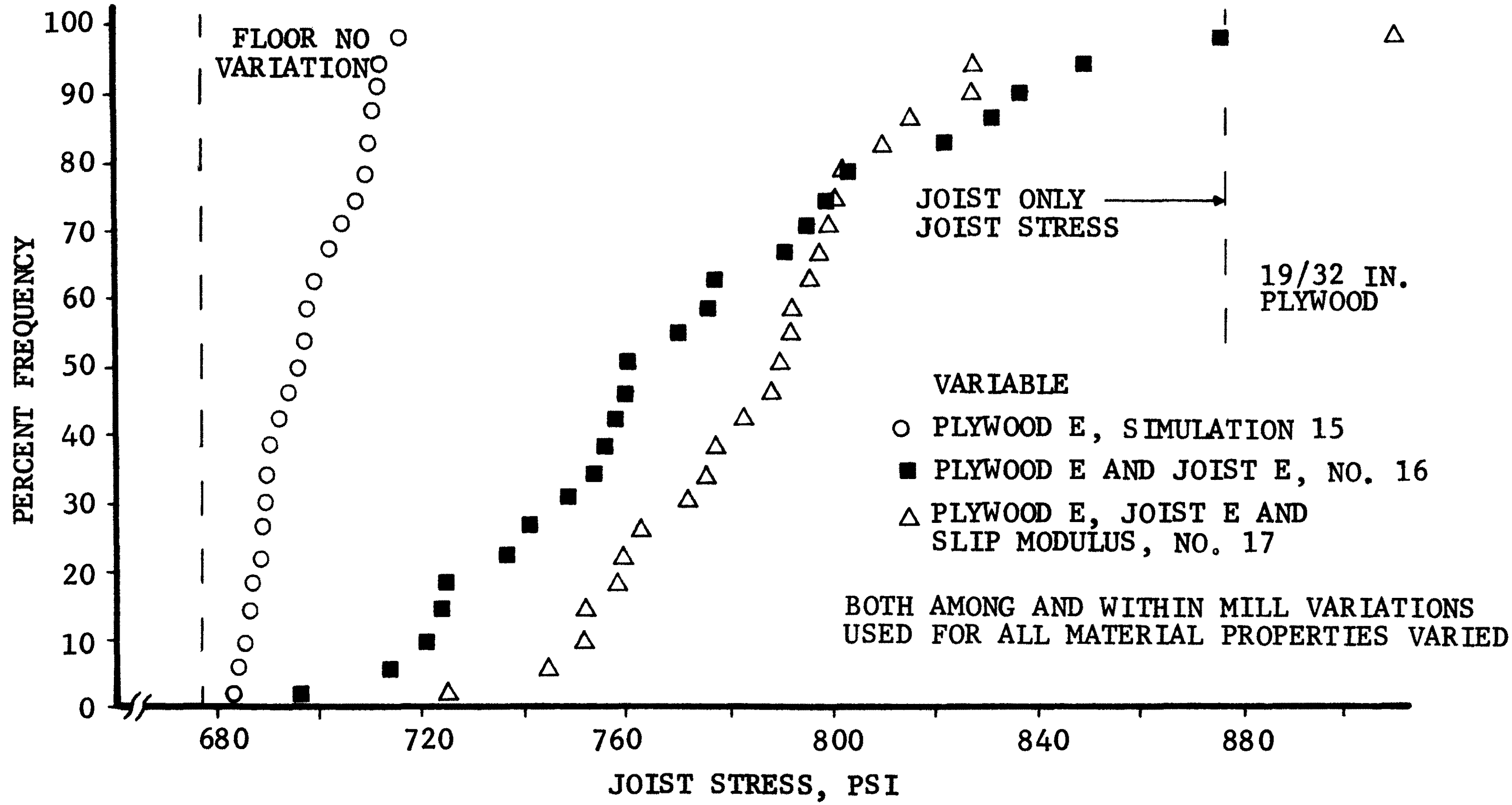


FIGURE 5.8

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATIONS 15, 16 AND 17 the response much more than does the plywood variability alone (Simulation 15). The mean of the maximum joist deflections increased from the 0.223 in. value for the condition of no material variation value to 0.226 in. for inclusion of plywood E variability only and to 0.267 in. for joist E variation only. This latter value is very near the 0.269 in. mean deflection resulting from the inclusion of both joist and plywood stiffness variability.

Figure 5.8 shows that of the 75 floors in these three simulations (15, 16 and 17), only one floor had a maximum joist stress larger than that given by the joist-only stress calculation. The joist having this high stress had an E of 1.81 x 10^6 psi, considerably above the 1.60 x 10^6 psi mean value. The crossing of the cumulative distribution curves for joist tensile stresses from Simulations 16 and 17 above the 70 percent frequency value is felt to be an example of the random process. Another simulation with the same specified input parameter values would likely not give this crossing. Simulations including more samples would give results which would be more reproducible. The plots do, however, show that the joist E variability has a greater influence on the joist response than does the plywood variability.

The dramatic decrease in deflections of floors with variable material properties resulting from the floor responding as an interacting unit rather than as a series of joists only is displayed in Fig. 5.9 for Simulation 17, which had joist E, plywood E and connector stiffnesses all varied.

Three simulations, 18, 19 and 20, were conducted to obtain an understanding of how the among and within mill variations affect the

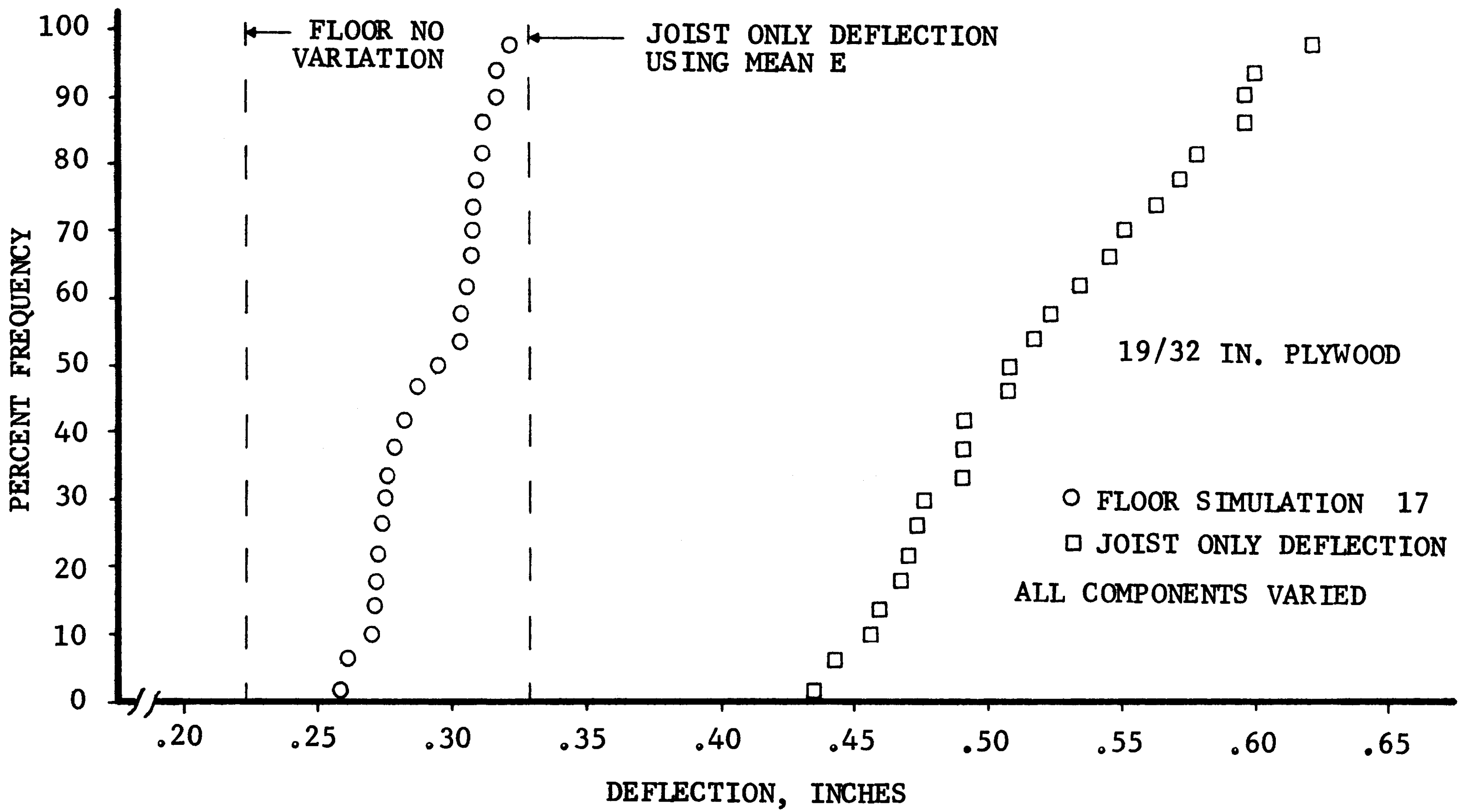


FIGURE 5.9
CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 17

floor response. These floors had the properties shown in Table 5.1. Because joist E variation was found previously to account for a majority of the deflection response variation, floors with only joist E variability were considered. Simulation 20 considered both within and among mill variations, Simulation 19 included only among mill variations, and Simulation 18 included only within mill variation. Simulation 19, which consideres only among mill variations, was not, of course, intended to represent an actual floor system since there is no variability of the joist E within the floor. The purpose of this simulation was to obtain an estimate of the effect of among mill variation only.

The response of these simulations is shown in Figs. 5.10 and 5.11. The among mill variation is shown to influence the response means less than does the within mill variation. This is due in part to the zero variability of the floor properties within each of the individual floors.

Variability of deflection response, as measured by the sample COV, ranged from 5.66 percent for 9 percent among mill COV only, 6.35 percent for 18 percent within mill COV only, and 7.27 percent for consideration of both of these variabilities. Note that even though the among mill variation was 50 percent of the within mill variation, it had nearly as much effect on the maximum deflection COV. The explanation for this is that the floor with among mill variations only did not have the possibility of weaker joists being adjacent to the stiffer joists which could relieve this weaker joist of a portion of the load tributary to it. Thus, the within-mill variation level was attenuated more by the lateral load distribution of the floor system than was the among-mill values.

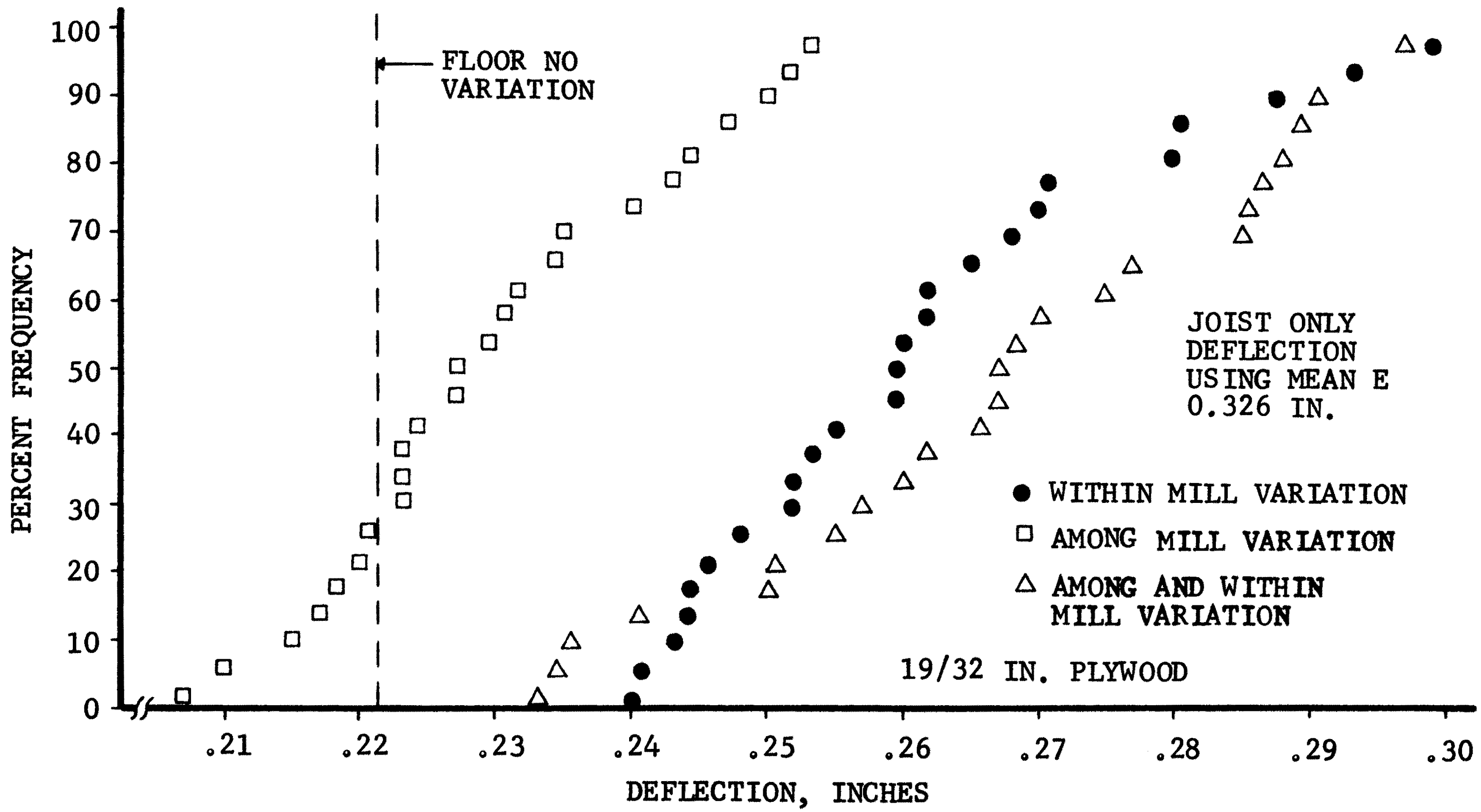


FIGURE 5.10

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATIONS 18,19 AND 20

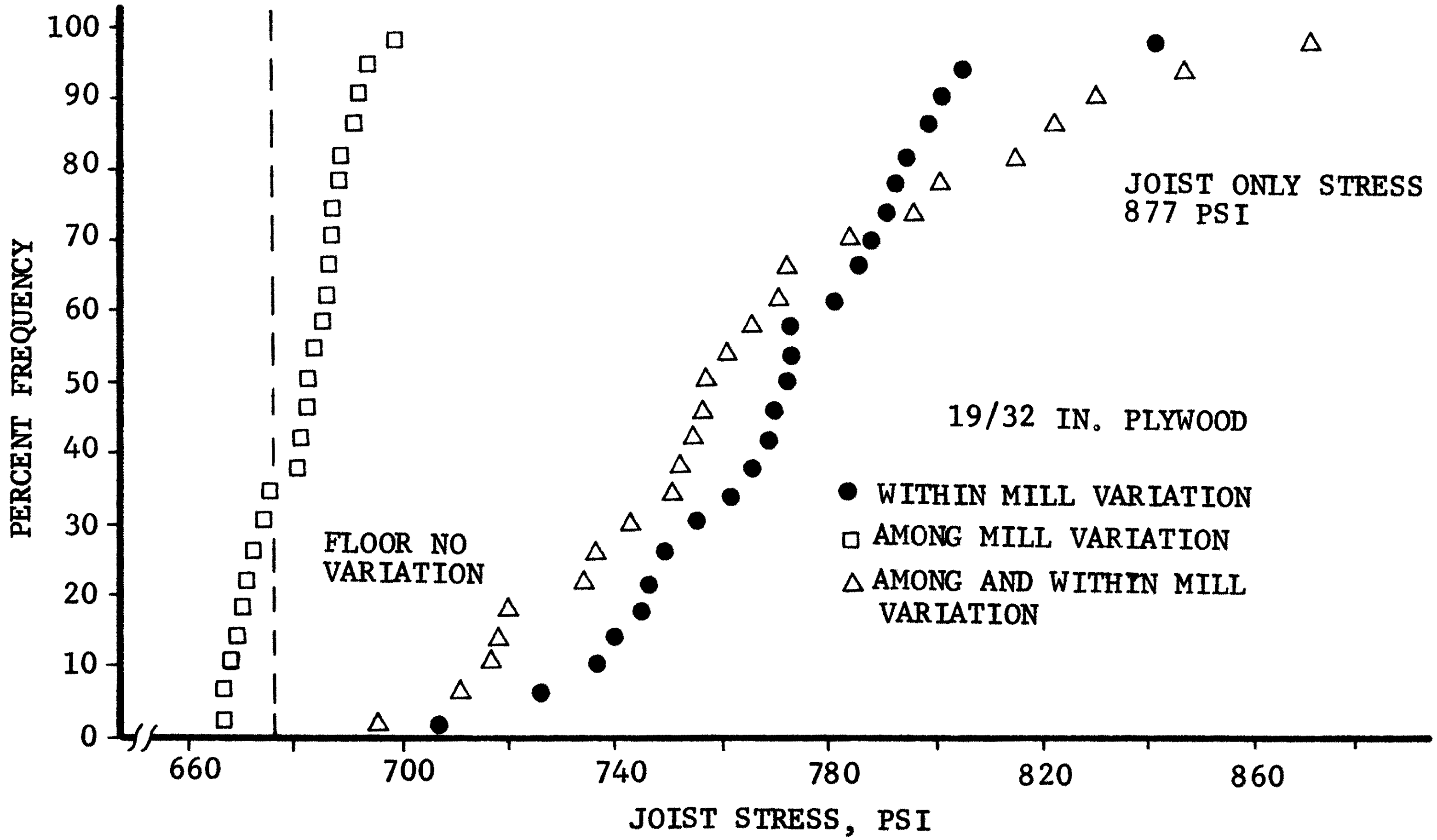


FIGURE 5.11

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATIONS 18, 19 AND 20

The mean of the maximum joist deflections increased much less (to 0.229 in. versus the 0.223 in. no variation value) with the among-mill variations than with the within mill variation value (mean maximum deflection is 0.261 in.). Consideration of only among mill variations should result in floors with nearly equal probabilities that all joists in the individual floor will be all above or all below the specified mean value. Thus it is expected that the among-mill variation only responses are distributed around the no variation value.

Among mill variability of joist stiffness also resulted in a negligible shift of the mean of the maximum joist tensile stresses. With 9 percent among mill variation only the mean maximum joist stresses increased only 3 psi above the 677 psi value for a floor with no variability versus an 89 psi increase resulting from a within mill variation of 18 percent. Only a small COV, 1.33 percent, resulted for this stress response. Little load sharing existed because of the uniform loading and the uniform joist stiffnesses of these floors. Variations in joist stresses resulted almost entirely from the changing ratio of the joist stiffness to the sheathing stiffness and the resulting variation in the relative contribution of these two components to the composite section strength. Lower stresses resulted from floors with lower joist stiffness. This behavior differs markedly from that which results from joist stiffness variation within a floor, a response which has been discussed in detail in Section 3.3.

The floor response variability and change in mean response values when both variabilities are considered are sometimes but not always close to the sum of the two variabilities considered separately. Addition of among-mill variability to within-mill variability

(Simulations 18 and 20) resulted in increased mean maximum deflections and joist tensile stresses of 0.006 in. and 5 psi, respectively, close to the 0.007 in. and 3 psi values above the no variation case observed with Simulation 19 with among-mill variation only. The 7.27 percent COV for maximum joist deflection with both variations considered was much less than the sum of the 6.35 and 5.66 percent values from Simulations 18 and 19, respectively. However, the variation of maximum joist stresses with both variabilities 5.85 percent exceeded the sum of the individual values of 4.00 and 1.33 percent for within- and among-mill variations only.

The above discussion demonstrates that the among mill and within mill variation result in considerable different system response.

5.2.4 The Effect of a Particle Board Third Layer on Floor Response

To determine the effect of a particle board third layer on the response of a minimum floor system, one-half inch thick particle board sheets were added to the floor configuration and component stiffness variabilities used in Simulation 13. The properties of this three layered system, Simulation 21, are given in Table 5.2. The value of the modulus of elasticity, E, of the particle board used in this study was obtained from the United States Department of Commerce, Commercial Standard CS 236-66 (25), and was 250,000 psi. The mean slip modulus between particle board and plywood was chosen as 3000 pounds per inch (12).

The maximum deflection and joist tensile stress responses of the floors of Simulations 21 (with particle board) and 13 (without particle board) are shown in Figs. 5.12 and 5.13. A considerable decrease in the maximum joist deflection within the floor system results with the

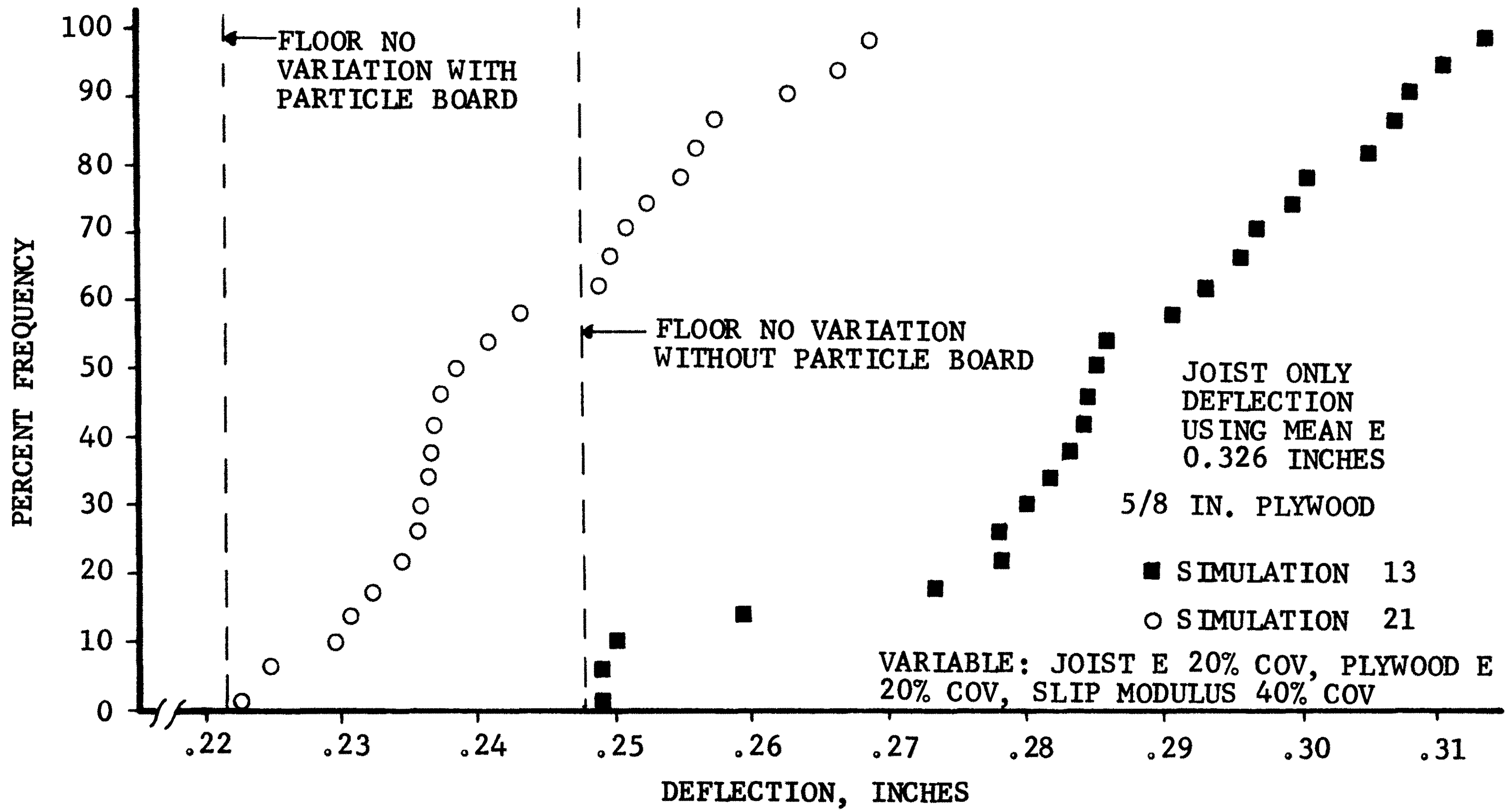


FIGURE 5.12

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATIONS 13 AND 21

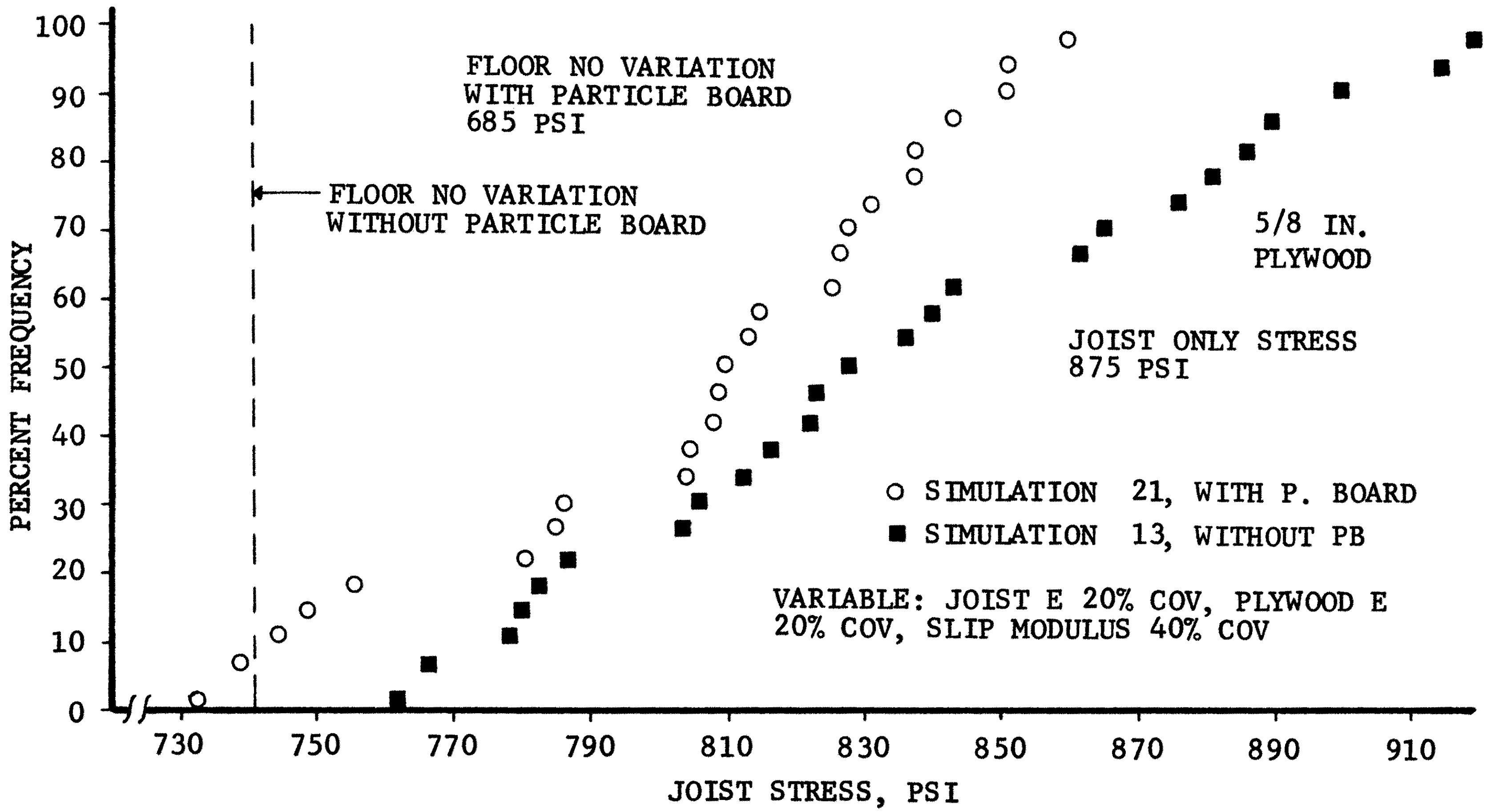


FIGURE 5.13

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATIONS 13 AND 21

addition of particle board (from a mean maximum value of 0.286 inches without particle board to 0.243 inches with particle board). However, the addition of the particle board was less effective in reducing the maximum joist stress. The mean of these maximum joist tensile stresses decreased slightly from 828 psi to 809 psi with the addition of the third layer.

Figure 5.14 shows the deflection reduction that exists by considering the three layered floor system as a unit instead of as a floor with joists only resisting the loading.

5.2.5 The Effect of Particle Board E Variability on Floor Response

To establish the effect that particle board E variability has on floor response, Simulation 22 with only the particle board stiffness varied was conducted. This simulation had the same average properties as those of the preceding Simulation 21. A fairly large level of variation (COV of 40 percent) was used for assigning the particle board stiffness to increase the effect of this parameter's variation. All properties of Simulation 22 are given in Table 5.2.

Figures 5.15 and 5.16 show the cumulative maximum (per floor) deflection and joist tensile stress distributions resulting from Simulation 22. Note the highly expanded horizontal scales of both figures. The variation in floor response, both joist deflection and maximum tensile stress, is seen to be very small. Thus, it is concluded that variability of particle board E produces only a very small variation in floor response.

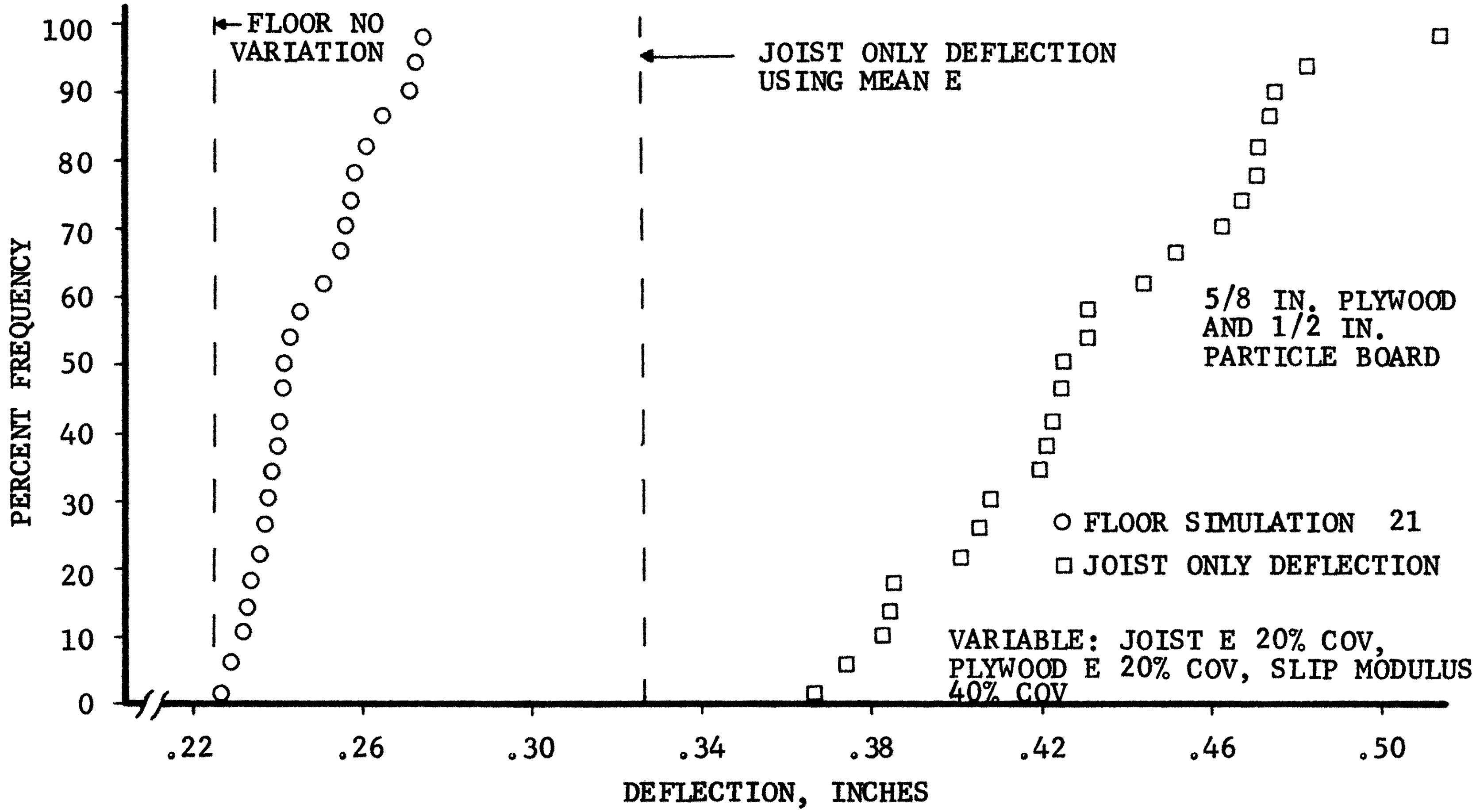


FIGURE 5.14

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 21

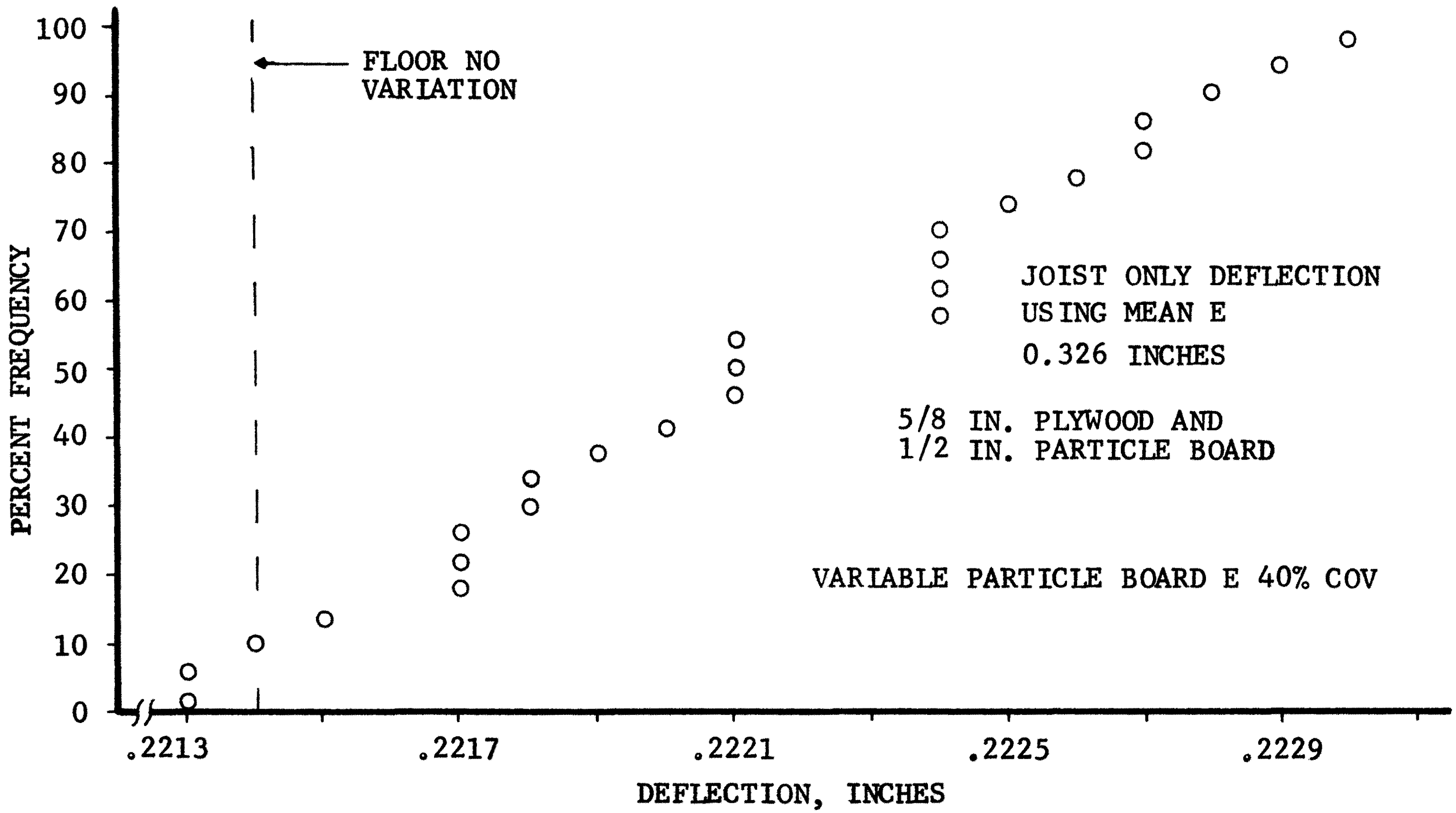


FIGURE 5.15

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 22

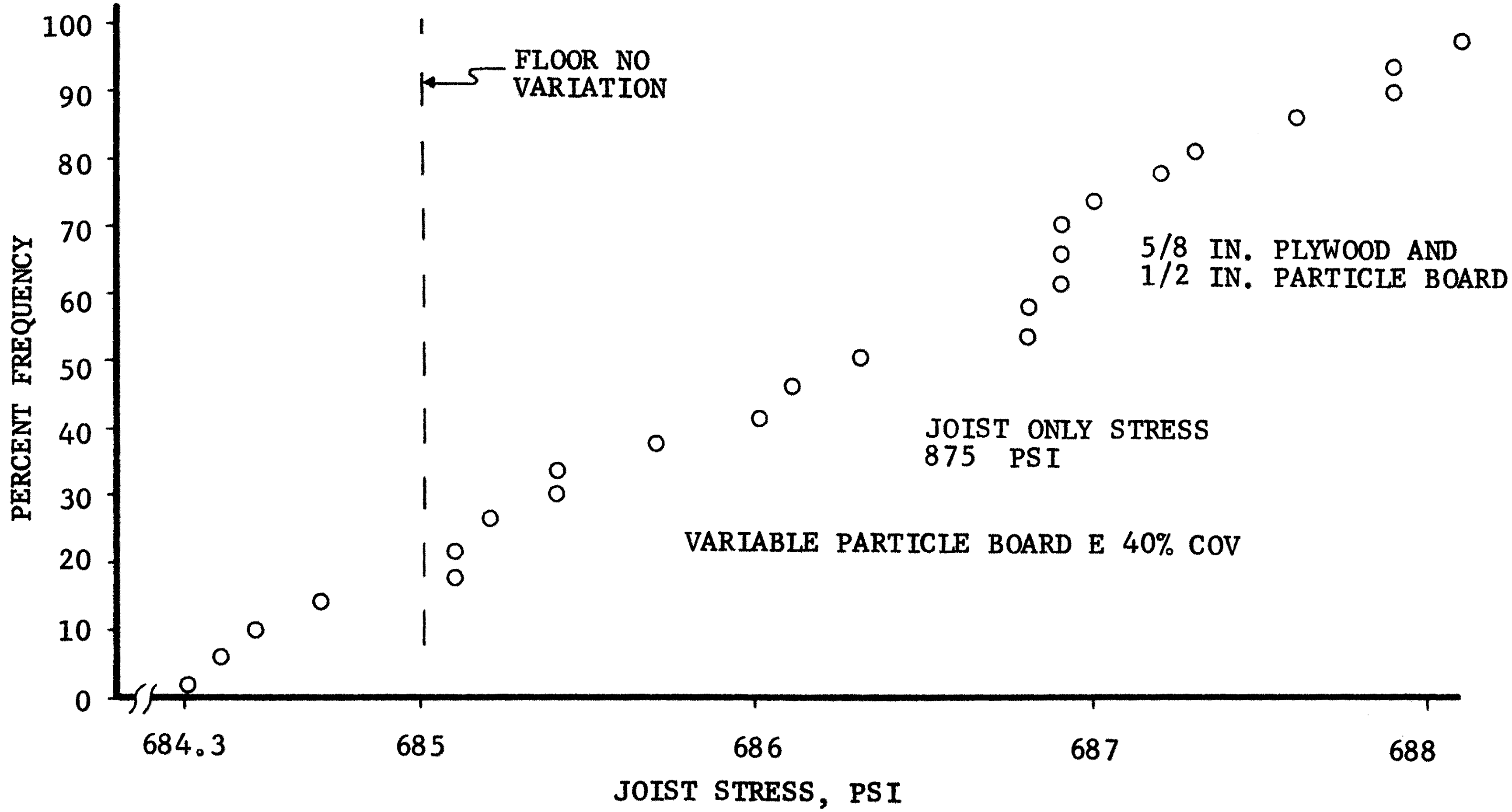


FIGURE 5.16
CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 22

5.2.6 Response of Floors with a Hardwood Third Layer

Simulations 23 and 24 included floors with 25/32 inch thick by 2 1/4 inch wide hardwood oak flooring placed perpendicular to the joists and atop one-half inch thick butted plywood.

The material properties used in these simulations are given in Table 5.2 and were mostly supplied by the National Forest Products Association. Slip modulus values were obtained from previous similar work at Colorado State University (12). A mathematical modeling including each piece of this third layer, which consists of narrow strips of various lengths, would be an expensive and time consuming task. It was therefore deemed necessary to model the strips as a continuous sheathing layer and to include two simulations which should bound the proper answer. To provide a lower bound on the maximum joist deflections and joist tensile stresses, the hardwood flooring was treated as a continuous third layer with no reduction in material properties to account for the softening effect of the flooring joints (Simulation 23). An upper bound on the maximum deflections and joist tensile stresses was supplied by treating the third layer as a continuous tightly butted tongue and groove gap (Simulation 24). This gap condition was modeled by reducing the flooring material perpendicular to the grain stiffness from the 80,000 psi material value to 10,000 psi.

The cumulative maximum (per floor) deflection and joist tensile stress distributions for Simulations 23 and 24 are shown in Figures 5.17 and 5.18. The maximum joist deflection range from a mean of 0.280 in. for the no gap condition to 0.309 in. for the tightly butted gap case (Fig. 5.17). About one-third of the floors with the tightly butted joints had at least one joist with a deflection larger than the joist-

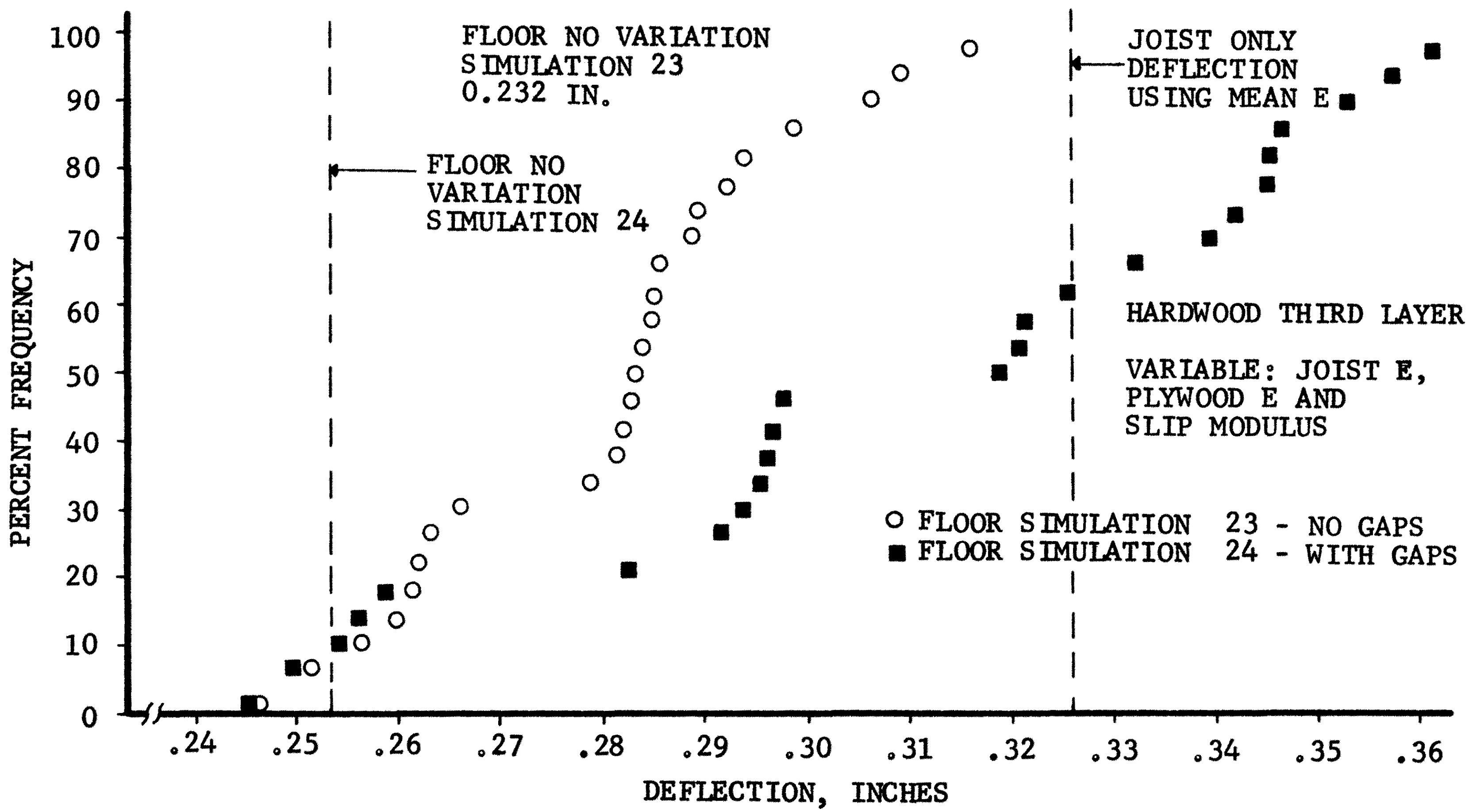


FIGURE 5.17

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 23 AND 24

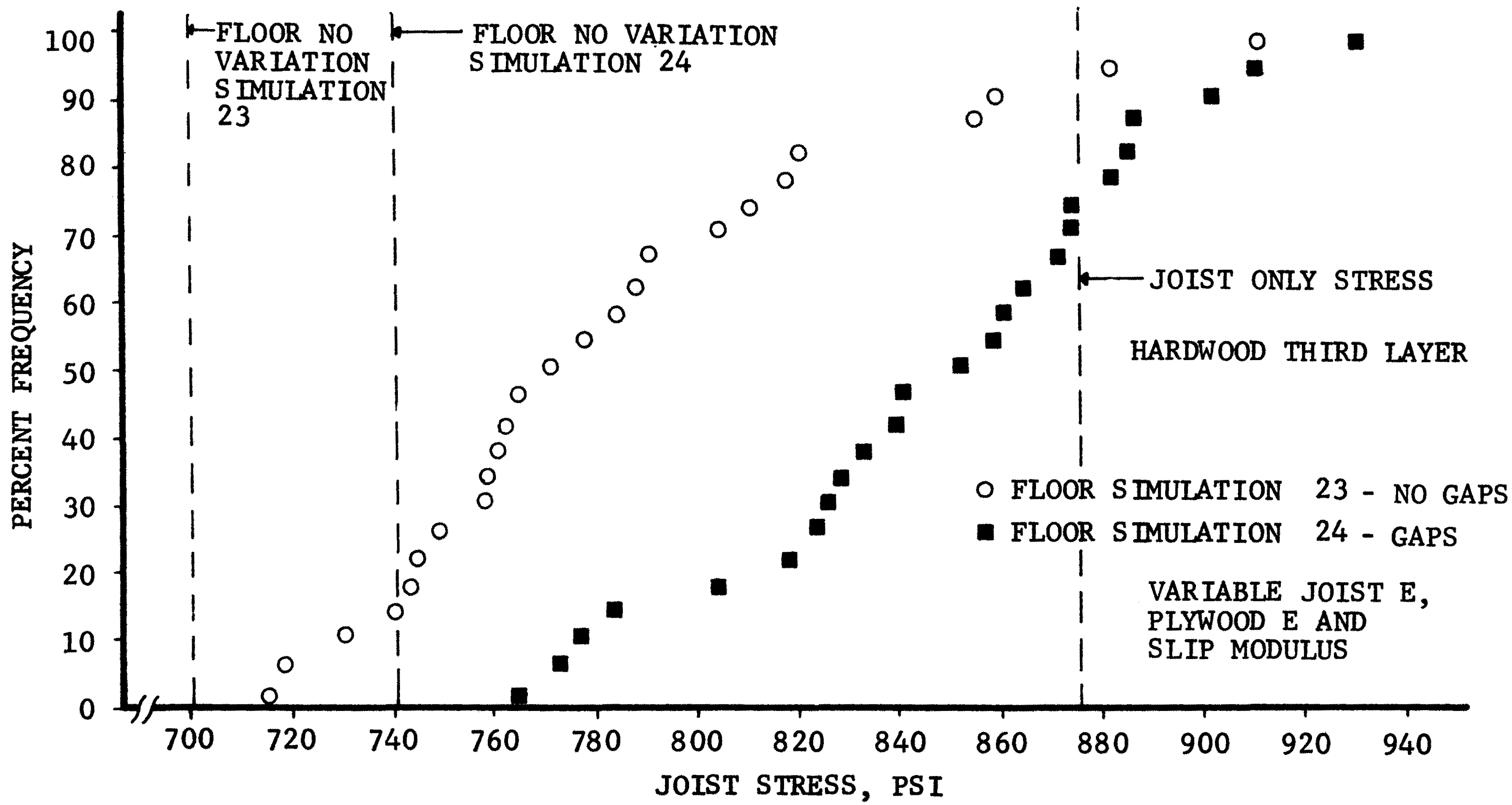


FIGURE 5.18

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 23 AND 24 only calculation gives using the mean joist E value would predict. The maximum joist tensile stress varies from a mean value of 784 psi to 846 psi for these same two extremes. The proper values are somewhere within the 0.029 in. deflection and 62 psi stress intervals. Although both of these intervals are fairly large, more information concerning material properties is needed for closer evaluation of effects the third layer of hardwood strips has on floor response.

The reduction in deflection that exists from treating the floor system as a unit rather than a collection of independent joists is displayed in Figs. 5.19 and 5.20.

The minimum floor simulations discussed in this chapter show that these floors, for the given loading and material variation values, have a greatly reduced response from what a joist-only consideration would predict.

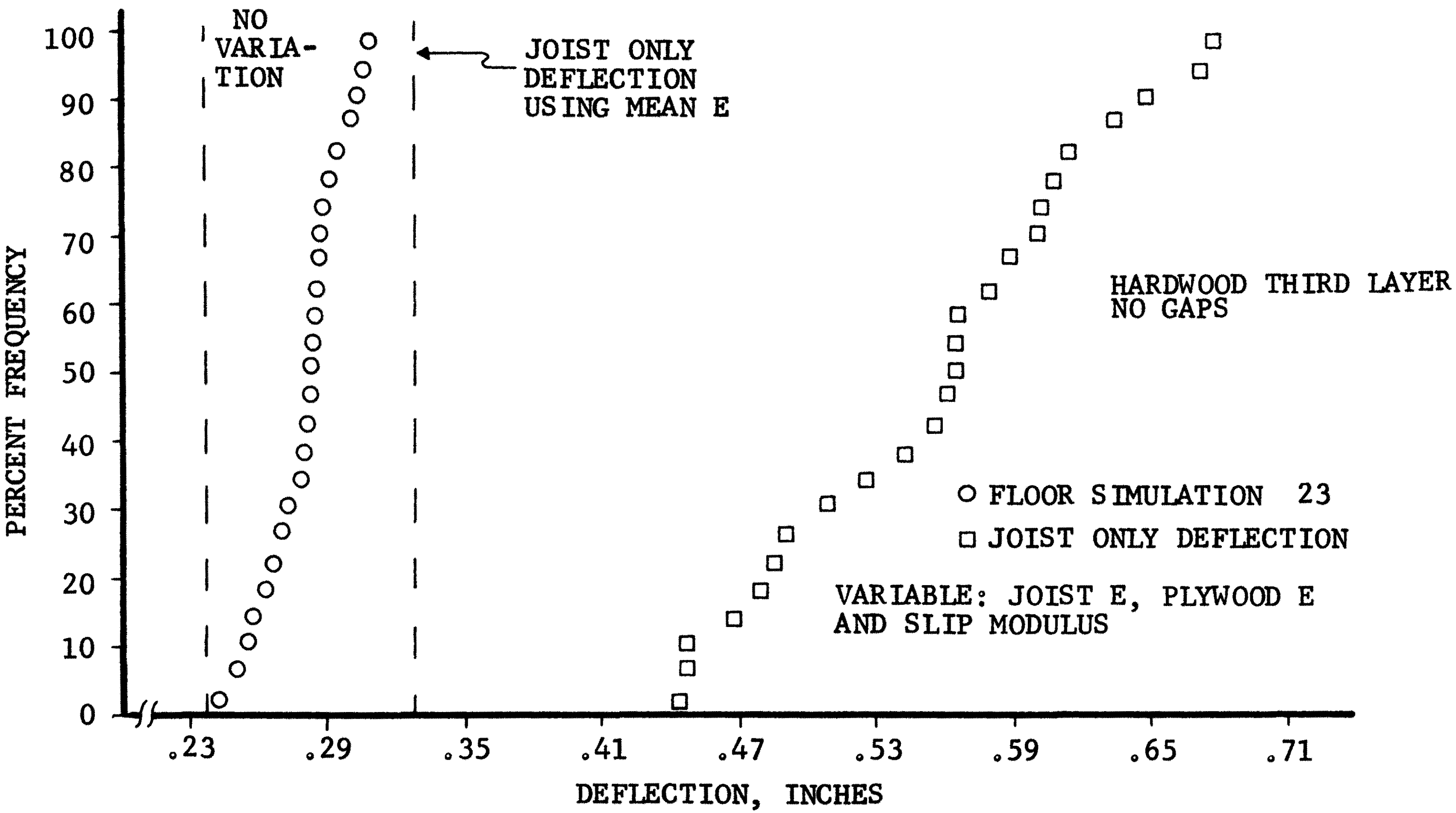


FIGURE 5.19

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 23

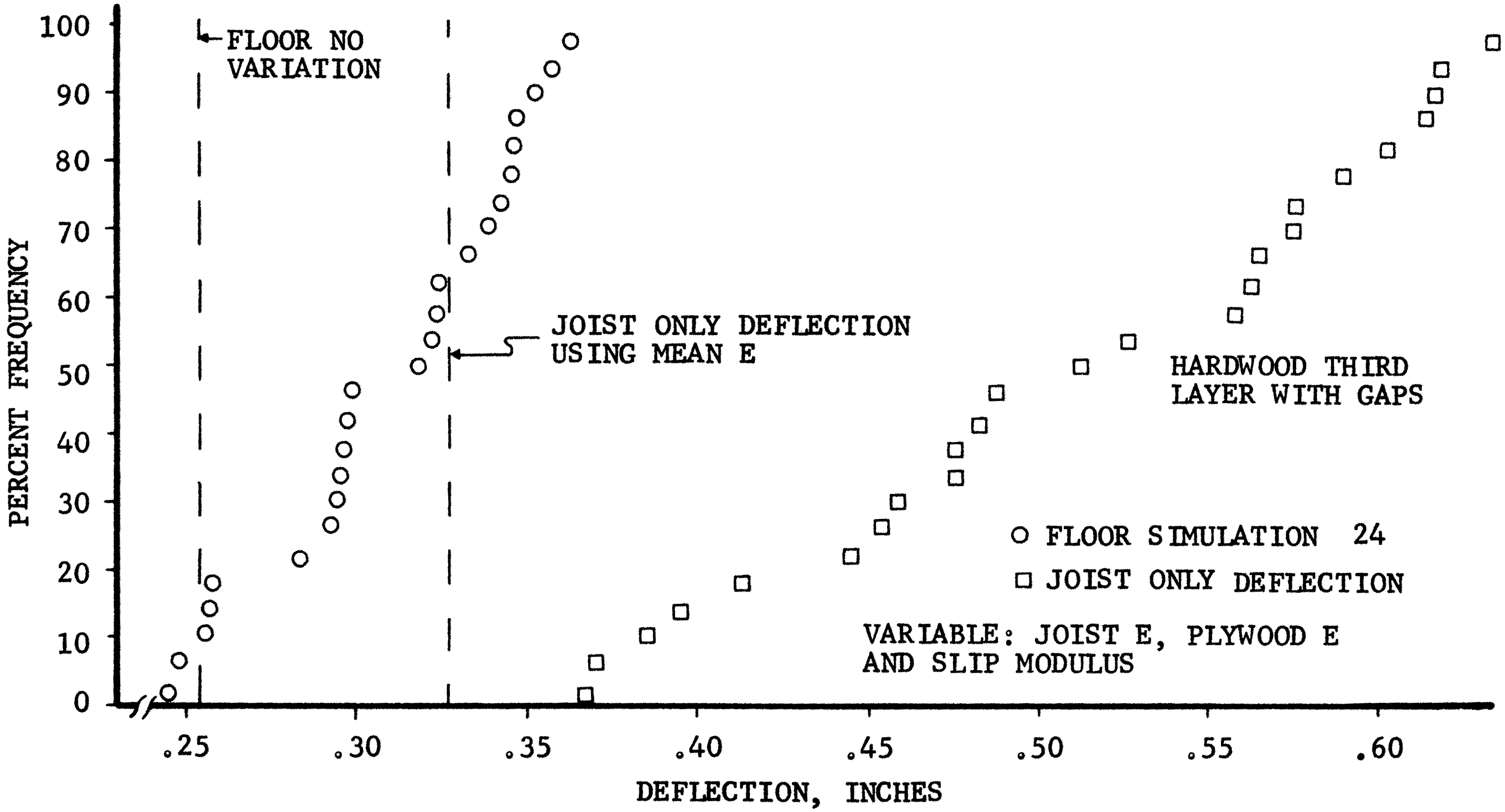


FIGURE 5.20

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 24

Chapter VI

SUMMARY AND CONCLUSIONS

6.1 Summary

This study consisted of Monte-Carlo simulation analyses of wood joist floor response to load with one or more variable material properties.

The purpose of this study were, first, to determine the effect of several component (joist E, plywood E, nail slip modulus) variabilities on floor response, second, to establish first approximations of the effect that certain geometric and loading conditions (tongue and groove versus butted plywood joints, concentrated versus uniform loading, plywood thickness, and two layers of sheathing) impose on floor response, and third, to simulate the expected response of some floors with variable component stiffnesses and with configuration and material strengths at or near the minimums allowed by some widely used U.S. design codes (including U.B.C. and B.O.C.A.).

The method used in these simulations included the selection of component stiffness values for each floor of a particular simulation utilizing a random number generator and a Weibull distribution with a previously specified mean and COV which describes the component's approximated stiffness distribution. Slip modulus variations were assigned independently of any joist and for sheathing variabilities. Once the floor component stiffnesses were assigned, the floors were analyzed for response to given loads using a finite element formulation of a mathematical model previously developed by others (2, 9, 10) at Colorado State University for analysis of multilayered floors. This mathematical formulation correctly models the incomplete composite action and lateral load sharing distribution of such multilayered floors having relative slip between each layer.

Response results for all twenty-five floors generated for each simulation of a given combination of component configuration and level of variability were then analyzed to determine floor response characteristics. In all simulations the sample size of twenty-five floors was used to keep most error of the estimate values below five percent. This level of statistical accuracy was reached for all but one simulation. The smallest practical sample size was desired to reduce the sizable computational expense which resulted when each of the floor systems in the simulation was individually analyzed.

The first study was conducted on a basic floor system (2 in. by 8 in. nominal joists, 16 in. on center, 12 feet long, 3/4 inch thick tongue and groove sheathing, and uniformly loaded with 40 psf), with independently varied joist, plywood and nail connector stiffnesses to isolate their effect on maximum floor deflections, joist tensile stresses and nail forces in the joist direction. The basic floor was then subjected to only a center point concentrated load, again with only one component stiffness allowed to vary, to determine response characteristics of concentrated loaded floors arising from component variation. The basic floor was then studied with butted (instead of tongue and groove) plywood joint conditions and again for a half inch (versus 3/4 inch) plywood thickness.

The last part of this study consisted of simulation analyses of minimum floors, including six simulations where various combinations of among-mill and within-mill variations were used to better simulate a large population of wood joist floors. As part of this last study, four three-layered systems were modeled, two with a particle board third layer and two with oak flooring third layers, to determine the effect of a third layer on the response characteristics.

The influence (mean maximum value and COV) of the 24 different combinations of floor configurations, component variability, and loading conditions considered on the mean and variation of maximum joist deflection and stress response within each floor are summarized in Table 6.1.

The characteristics of material variability and their effect on the response of maximum deflection (mean and COV) and the maximum joist tensile stress (mean and COV) for the basic floor and some variations of the basic floor are given in Table 6.2. Component stiffness variability and response means and variations have been assumed to be linearly related. The larger multiplication factor or slope for these linear approximations identify the more critical combinations of component variabilities and loading conditions. These multiplication factors or slope values should be reasonably accurate for slight variations of the conditions for which these values were computed.

A comparison of the specified mean and COV values for the varied floor components with those resulting from the Monte-Carlo simulation procedures for each of the 24 simulations in this study are given in Appendix B. The validity of the trends determined in this study is demonstrated by the error of the estimate values for each simulation displayed in Table 6.3.

Plots of the floor response for three simulations (2, 3 and 22) on normal distribution paper are shown in Appendix D. These simulations were chosen to represent the medium, highest and lowest,

TABLE 6.1 Summary of Floor Responses

Simulation Number	Description	COV of Joist E	The Component Plywood E	Percent Slip Modulus	Response of The Floors * Max. Joist Deflection Inches		Max. Joist Stress PSI	
					Mean	COV	Mean	COV
1	Basic Floor	10	-	-	0.190	3.25	698	3.56
2	Basic Floor	20	-	-	0.201	5.99	759	6.46
3	Basic Floor	40	-	-	0.233	13.50	884	10.25
4	Basic Floor	-	20	-	0.186	1.26	664	1.03
5	Basic Floor	-	-	60	0.205	5.38	699	2.93
6	Basic Floor	20	10	40	0.208	8.01	772	5.85
7	Basic Floor Conc. Load	20	-	-	0.121	6.56	563	9.32
8	Basic Floor Conc. Load	-	20	-	0.120	5.94	564	5.11
9	Basic Floor Conc. Load	-	-	60	0.123	6.54	564	2.17
10	Basic Floor Butted Plywood	20	-	-	0.237	5.08	834	4.11
11	Basic Floor 1/2 inch Plywood	20	10	40	0.232	5.68	794	7.16

*More detailed response is given in Table 6.3.

TABLE 6.1 Continued

Simulation Number	Description	COV of the Component, Percent: Joist E	Plywood E	Slip Modulus	Response of The Floors *: Max. Joist Deflection Inches: Mean	COV	Max Joist Stress PSI: Mean	COV
12	5/8 Plywood	20	-	-	0.274	5.44	835	4.07
13	5/8 Plywood	20	20	40	0.286	6.56	836	5.67
14	1/2 Plywood	20	20	60	0.277	7.27	801	5.22
15	19/32 Plywood	-	11,13**	-	0.226	2.26	697	1.47
16	19/32 Plywood	9,18	11,13	-	0.269	7.45	773	5.88
17	19/32 Plywood	9,18	11,13	60	0.291	7.73	788	6.38
18	19/32 Plywood	0,18	-	-	0.261	6.35	766	4.00
19	19/32 Plywood	9,0	-	-	0.229	5.66	680	1.33
20	19/32 Plywood	9,18	-	-	0.267	7.27	771	5.85
21	5/8 Plywood and P.B.	20	20	40	0.243	5.27	805	4.64
22	5/8 Plywood and P.B.	-	40+	-	0.222	0.23	685	0.32
23	1/2 Plywood and Oak	9,18	11,13	40	0.280	6.53	784	6.42
24	1/2 Plywood and Oak	9,18	11,13	40	0.309	11.8	846	5.19

* All Minimum Floors
** Among Mill, Within Mill
P.B. = Particle Board
Oak = Hardwood Oak Flooring
\+ = Particle Board Variation Only

NOTE: Simulation 23 - Oak flooring has an E in the perpendicular to flooring direction of 80,000 psi.

Simulation 24 - Oak flooring E in the perpendicular direction = 10,000 psi.

TABLE 6.2 Summary of Component Versus Response Variabilities

Loading and Component Varied	Simulations Supplying Information	Multiplication Factors for Mean Response Values: Max. Joist Deflection	Max. Joist Stress	Max. Nail Force
Uniform Loading 40 psi				
Joist E	1,2,3	0.00560	0.00758	0.00408
Plywood E	4	0.00054	0.00029	0.00067
Slip Modulus	5	0.00179	0.00101	0.00294
Conc. Load 550 Pounds				
Joist E	7	0.00095	0.00048	0.01677
Plywood E	8	0.00084	0.00062	0.01696
Slip Modulus	9	0.00069	0.00022	0.00394

$$\text{Mean Maximum Response} = \text{Mean Maximum Response Without Variation} \left(1 + \left(\text{Multiplication Factor}\right)\left(\text{Component COV Percent}\right)\right)$$

Mean Maximum Responses Without Variation

Condition	Joist Deflection Inches	Joist Stress PSI	Nail Force Pounds
Basic Floor Uniform Loading	0.184	660	298
Basic Floor Concentrated Load	0.1185	557	119

TABLE 6.2 Continued

Loading and Component Varied	Simulations Supplying Information	Multiplication Factors for Mean Response Values: Max. Joist Deflection	Max. Joist Stress	Max. Nail Force
Uniform Loading 40 psf				
Joist E	1,2,3	0.337	0.284	0.193
Plywood E	4	0.063	0.051	0.085
Slip Modulus	5	0.090	0.049	0.140
Conc. Load 550 Pounds				
Joist E	7	0.328	0.466	0.161
Plywood E	8	0.297	0.255	0.118
Slip Modulus	9	0.109	0.036	0.362

$$\text{COV of Mean Max. Response} = \left(\text{Multiplication Factor}\right)\left(\text{Component COV Percent}\right)$$

TABLE 6.3 Simulation Results

Simulation Number	Deflection COV, Percent	Mean Maximum Deflection	Magnitude of Error* of the Estimate	
	Joist Deflection		Magnitude	Percent of Mean Deflection
1	3.25	0.190	0.00256	1.341
2	5.98	0.201	0.00496	2.471
3	13.49	0.233	0.01299	5.571
4	1.26	0.186	0.00097	0.522
5	5.38	0.204	0.00454	2.220
6	8.01	0.208	0.00695	3.343
7	6.56	0.121	0.00327	2.709
8	5.94	0.120	0.00296	2.453
9	6.53	0.123	0.00333	2.699
10	5.08	0.237	0.00498	2.098
11	5.68	0.231	0.00543	2.344
12	5.43	0.278	0.00625	2.244
13	6.56	0.286	0.00773	2.707
14	7.27	0.276	0.00830	3.002
15	2.26	0.226	0.00210	0.933
16	7.45	0.269	0.00829	3.007
17	7.73	0.290	0.00928	3.193
18	6.35	0.261	0.00685	2.621
19	5.66	0.229	0.00537	2.337
20	7.27	0.267	0.00803	3.002
21	5.27	0.243	0.00529	2.177
22	0.23	0.222	0.00021	0.096
23	6.53	0.280	0.00755	2.696
24	11.81	0.309	0.01507	4.875

*All error terms are based on a 95% confidence limit. The true mean value is expected to be outside of the interval extending from one error of the estimate value above to one such value below the computed sample value only five percent of the time.

TABLE 6.3 Continued

Simulation Number	Joist Stress COV, Percent	Mean Maximum Joist Stress PSI	Magnitude of Error* of the Estimate	
			Magnitude	Percent of Mean Joist Stress
	Joist Tensile Stress			
1	3.56	697.8	10.2581	1.470
2	6.46	759.4	20.2686	2.668
3	10.25	884.0	37.3982	4.230
4	1.03	663.8	2.8227	0.425
5	2.94	699.0	20.4609	2.927
6	5.85	772.2	18.6464	2.414
7	9.32	562.5	21.6445	3.847
8	5.12	563.9	11.9125	2.112
9	2.16	564.4	5.0472	0.894
10	4.11	833.5	14.1560	1.698
11	7.16	793.8	23.4587	2.955
12	4.07	835.2	14.0253	1.679
13	5.67	835.5	19.5535	2.340
14	5.22	800.7	17.2673	2.156
15	1.47	696.6	4.2391	0.608
16	5.88	772.5	18.7614	2.428
17	6.38	787.5	20.7612	2.636
18	4.00	766.4	12.7514	1.653
19	1.33	679.8	3.7317	0.548
20	5.85	771.4	18.5100	2.414
21	4.64	805.4	15.4347	1.916
22	0.32	685.8	0.9164	0.133
23	6.42	784.3	20.8096	2.653
24	5.18	846.1	18.1171	2.141

*All error terms are based on a 95% confidence limit.

respectively, error of the estimate terms for maximum joist deflections which are contained in Table 6.3. These plots indicate that the response is approximately normal.

6.2 Conclusions

The following major conclusions can be reached based on the results of the simulations described in Chapter III, IV, and V:

1. With uniform loading, the variability of the maximum joist deflection and maximum joist tensile stress responses within each floor is predominately caused by the variation of the joist modulus of elasticity (E) values.
2. With either uniform or concentrated loading, the maximum nail force variation is affected to a considerable degree by the variation in the joist E, the plywood E and the slip modulus.
3. For concentrated loadings, the variability of maximum deflection and joist tensile stress response is mostly affected by both the variability of the joist E, especially for the loaded and the two adjacent joists and by the variation in the plywood E values.
4. For uniform loads, the ratio of the E for the critical joist to the average E value of the two adjacent joists, $E_j/(1/2(E_{j-1}+E_{j+1}))$, is approximately linearly related with the maximum joist tensile stress of that same floor.
5. The joist of a uniformly loaded floor system having the highest flexural stress also will usually have a higher than average stiffness.

6. A uniformly loaded floor system with tightly butted sheathing joints gives higher maximum deflections and joist stresses but lower maximum nail forces than does the same system with tongue and groove plywood joints.
7. Maximum plywood stresses are small for all of the simulations conducted in this study (see Appendix F).
8. The maximum joist deflections of all the minimum floor configurations and material distributions studied are almost always below the joist-only deflection calculated using the mean E.
9. Large reductions in predicted deflection response exists when the floor is analyzed as an interacting system of components as compared to the results of a joist-only analyses.
10. Particle board used as a third layer considerably reduces the maximum joist deflections and only slightly reduced the maximum joist tensile stresses.
11. Variability of the particle board E produces only very small changes in the mean and COV response of the floor.
12. When both among and within mill material property distributions are considered, the within mill distribution will account for nearly all of the increase in mean deflection response values and joist tensile stress variability. However, both sources of variability increase the variability of the response.

6.3 Future Research Needs

The project reported herein demonstrates that the Monte-Carlo simulation method is a very useful tool in examining floor response characteristics. Its use with a valid mathematical model can provide information which is impossible, or at best, impractical to obtain from a physical testing program.

Several needed improvements can be identified which would make the simulation method more valuable and useful in predicting floor response to load. These fall into the following three broad categories: improvement of the mathematical model for floor analysis incorporated into the simulation studies, improved information on component variabilities, and modification of the simulation method itself.

For the method itself, future work is needed to better determine the number of floor samples which are needed to obtain the desired level of reliability for the predictions. This is needed to minimize the computation costs. The sample size needed no doubt depends upon the relative importance of the component varied in determining the floor response and the component variability level as well as on the level of confidence desired in the solution.

The model needs to be modified so that connector slip modulus mean and variabilities can be assigned as a function of the stiffness properties of the joist and sheathing elements adjoining the slip plane.

Logic could be included in the program which stops a simulation when enough floors had been generated and analyzed to give a specified accuracy level for all response characteristics desired.

Variability of load intensity over the surface of the floor could be included in the model to better match the typical loading patterns which actually exist on floors.

The capabilities of the simulation method heavily depend on those of the mathematical model and analysis methods. Improved efficiency of the analysis methods become very important when time savings can be multiplied many times, as they would be in the simulation procedure. A method to realistically determine floor failure capacities is needed to allow the simulation method to be used to study floor safety statistics in addition to the serviceability statistics which were the primary concern in the present study.

One of the weakest areas in the use of the simulation studies is the limited amount of data on material geometry and strength variability and mean stiffness values. These should be based on large quantities of samples; quantities large enough that among and within mill distributions can be accurately obtained for different species and products.

Use of the simulation method for wood joist floors does point the way toward a possible design method which could be based on providing floors with a specified level or probability of satisfactory service and safety performance. The form of this design method is undefined at present. It would appear that a systematic parametric study which would result in refinement and extension of the relationships between input and output characteristics, such as those reported in Table 6.2, would be most useful. A design method which directly or indirectly recognize both the benefits of floor component interaction and the effects of material variabilities would allow the use of minimum member sizes and properties along with the maximum joist spacings consistent with desired performance levels.

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APPENDIX A RESPONSE VARIATIONS WITHIN INDIVIDUAL FLOORS OF THE BASIC FLOOR SIMULATIONS

A second method of presenting the distributions of the floor response is included in this appendix. This presentation is most useful for uniformly loaded floors. The cumulative plot of average joist deflection and joist tensile stress within each floor are given for simulations one through five. Such plots give more information on the behavior of the average joist within each floor as opposed to the most critical joist.

To convey a measure of the variability of the joist response within each floor, an interval extending one sample standard deviation above and below the sample mean value for the floor is shown for each floor. Only these maximum values were shown in the plots of Chapter III.

The figures of this appendix show that the standard deviation of response within a floor is quite random across the average response distribution. Also evident is that the maximum response is significantly greater than the mean response values. The maximum response values within the floor are quite highly correlated with the placement of the floor within the average response distribution. Maximum floor response characteristics were more variable than the average response variations, especially in cases when joist stiffness was varied. The average joist stress varied little when other than joist stiffness was varied.

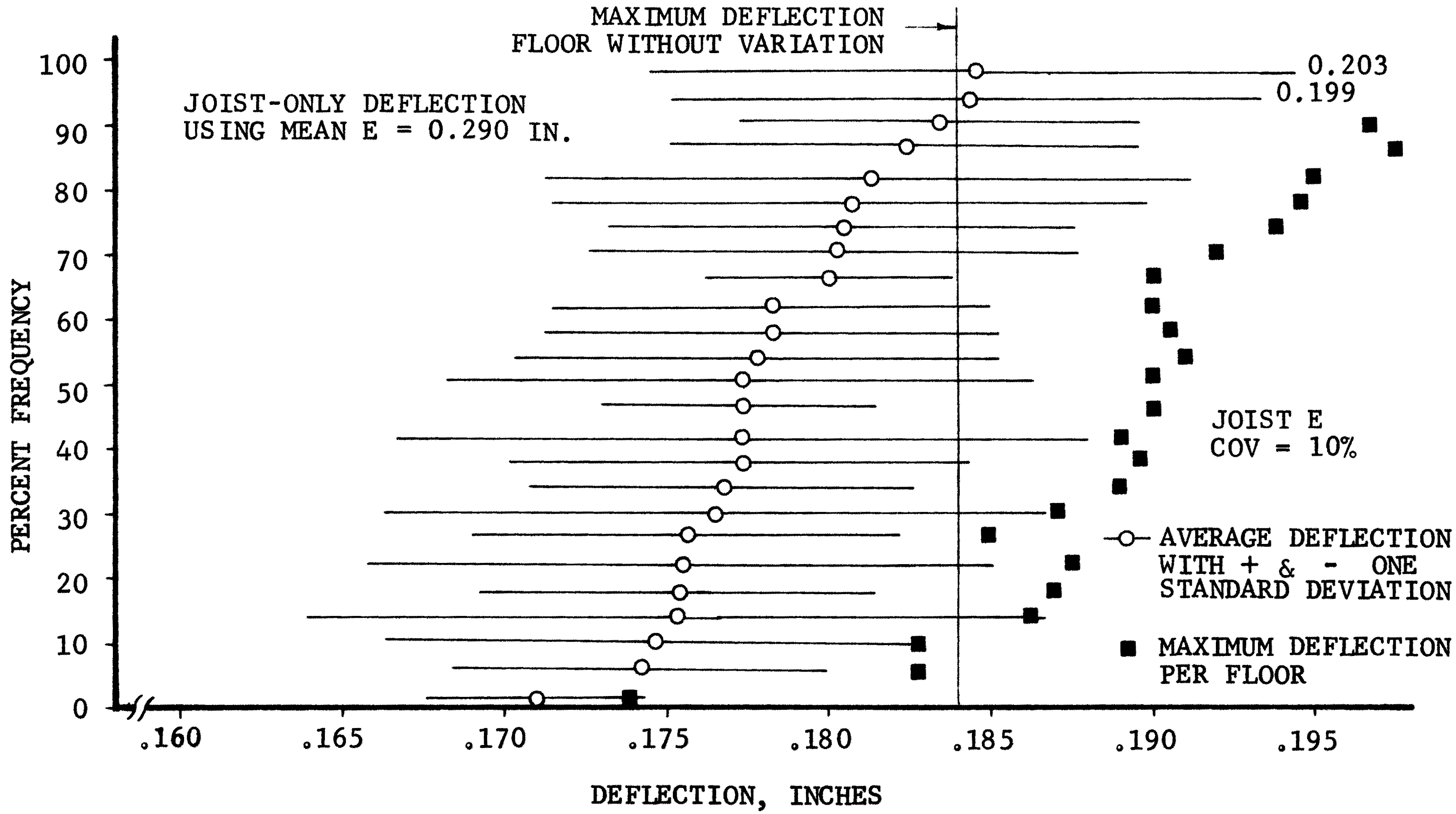


FIGURE A-1

CUMULATIVE AVERAGE DEFLECTION DISTRIBUTION - SIMULATION 1

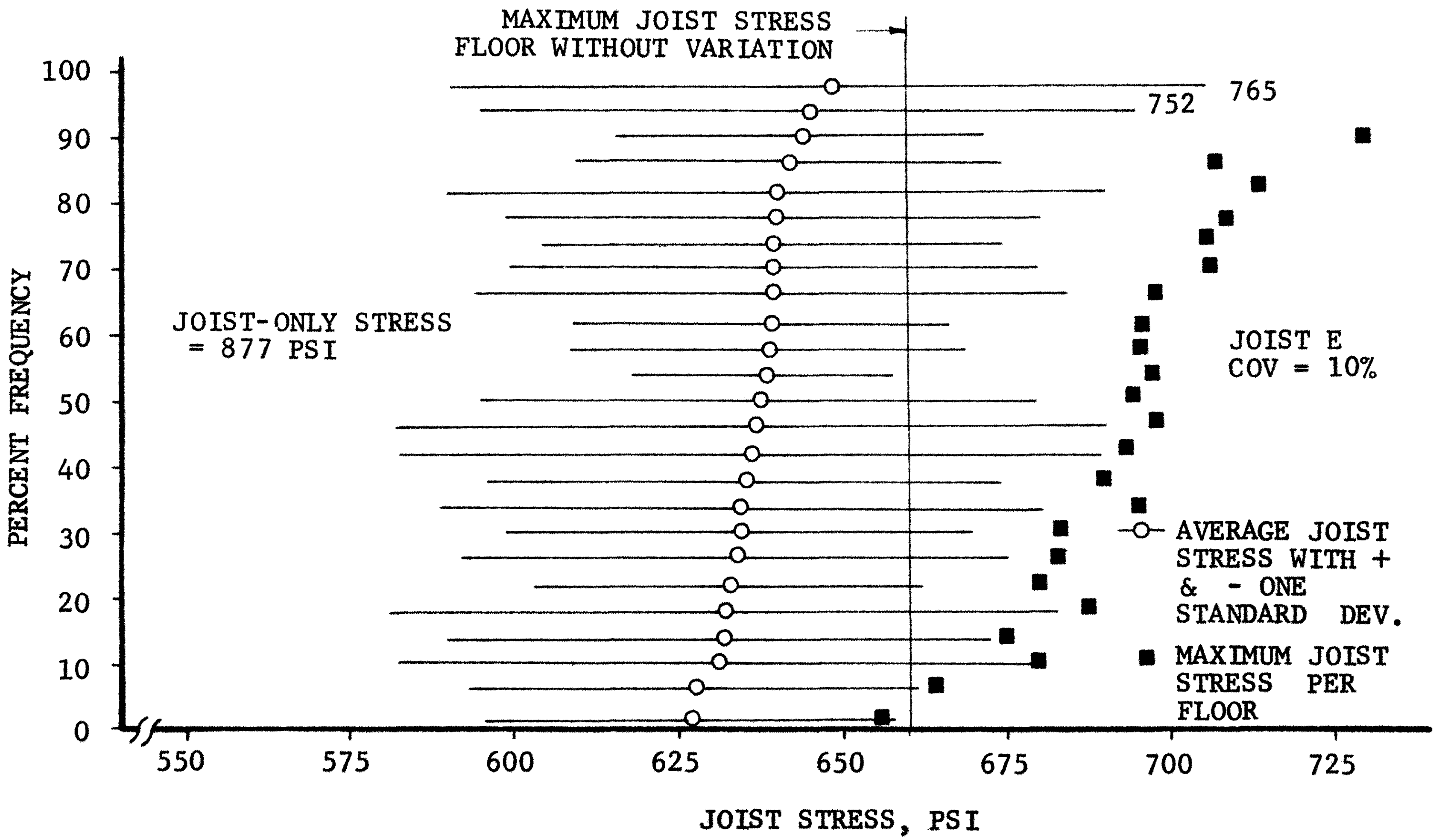


FIGURE A-2

CUMULATIVE AVERAGE JOIST STRESS DISTRIBUTION - SIMULATION 1

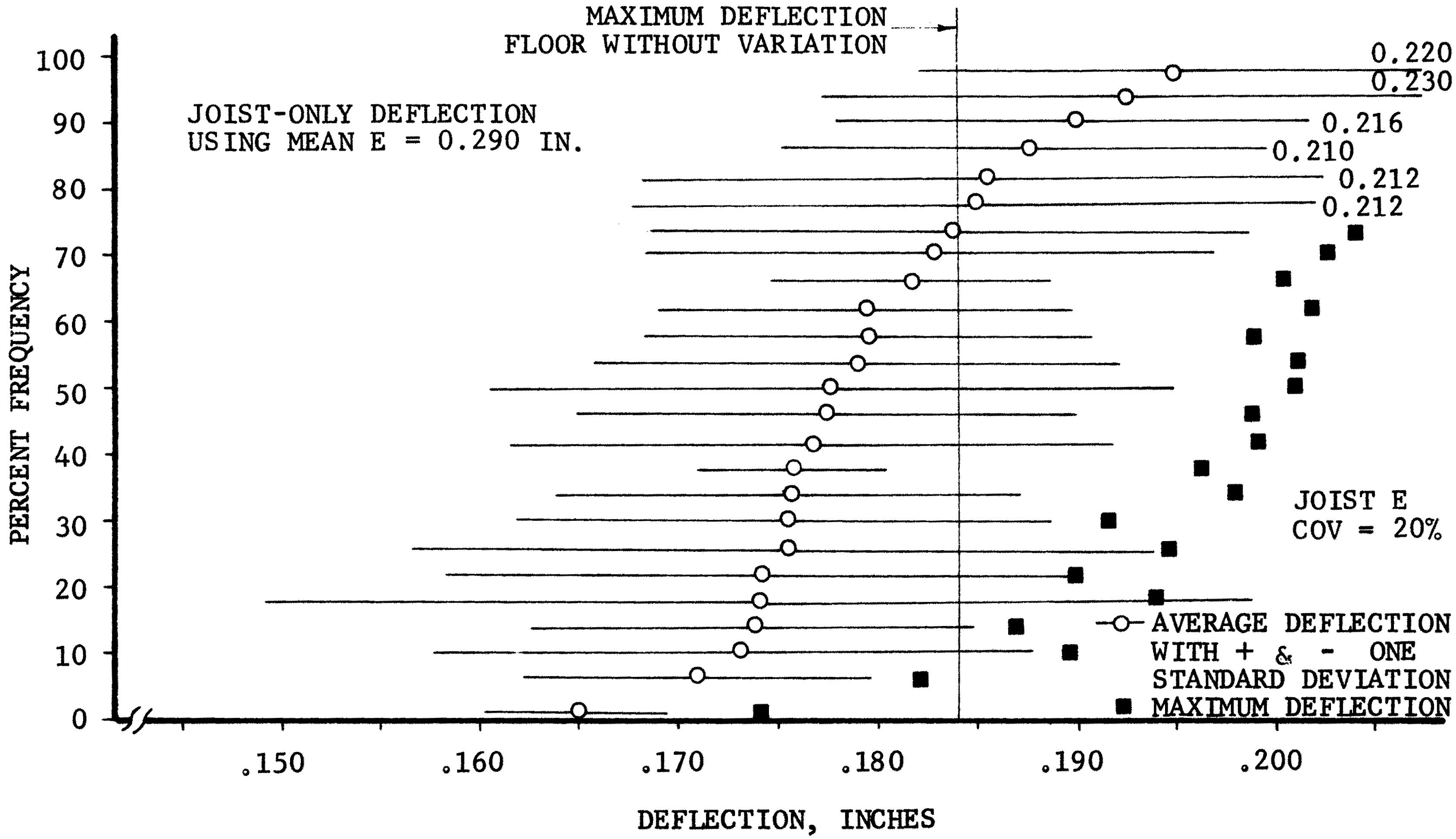


FIGURE A-3

CUMULATIVE AVERAGE DEFLECTION DISTRIBUTION - SIMULATION 2

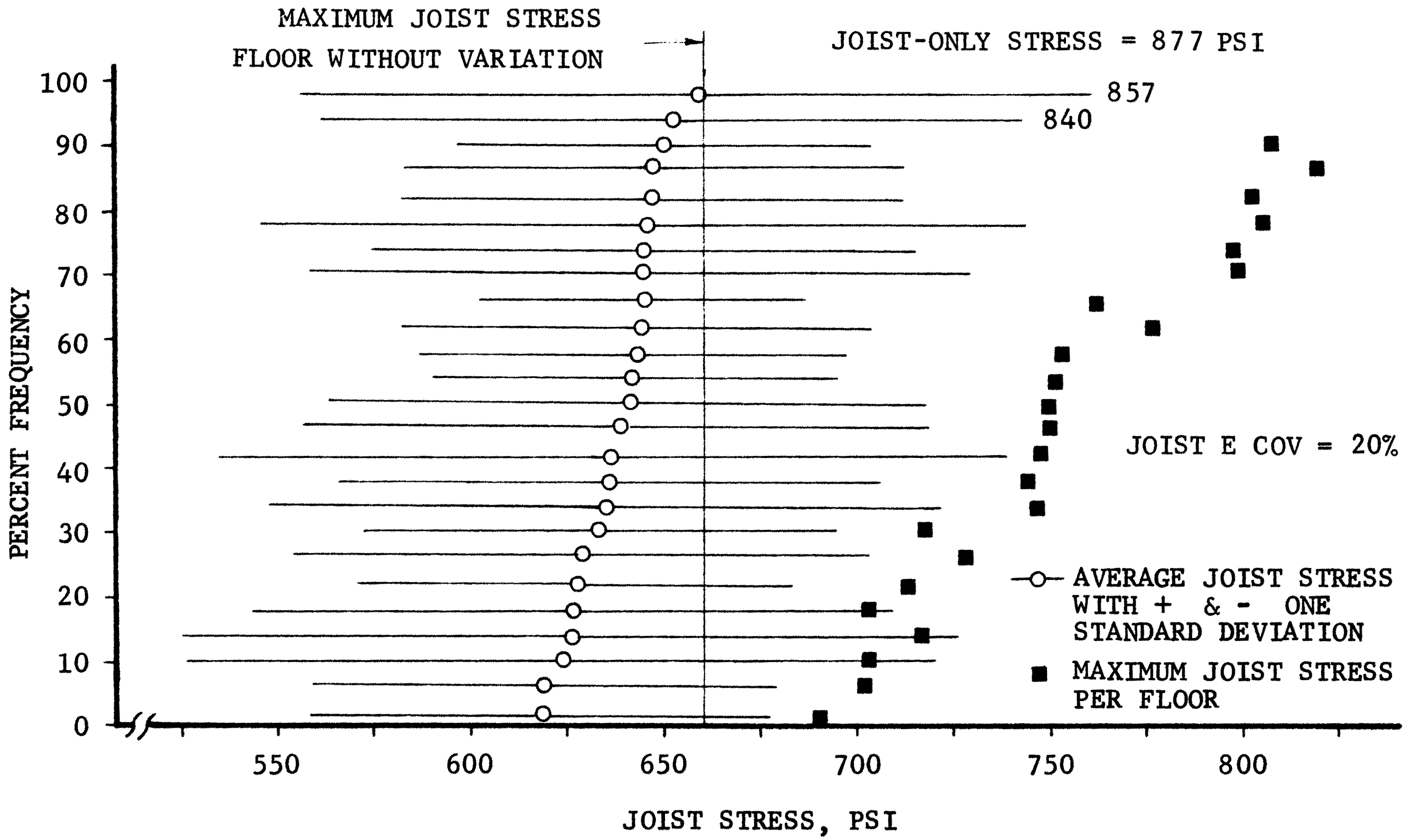


FIGURE A-4

CUMULATIVE AVERAGE JOIST STRESS DISTRIBUTION - SIMULATION 2

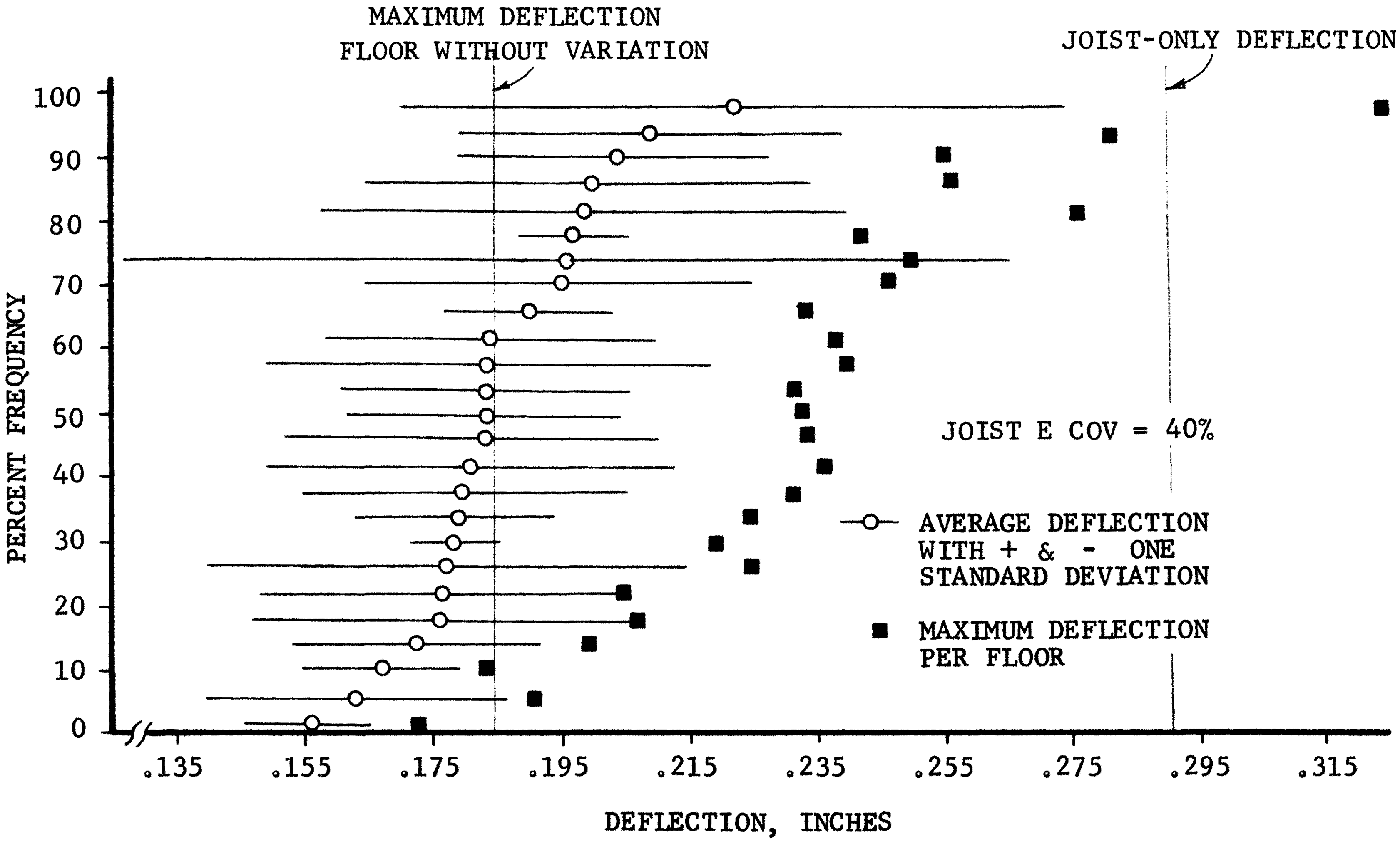


FIGURE A-5

CUMULATIVE AVERAGE DEFLECTION DISTRIBUTION - SIMULATION 3

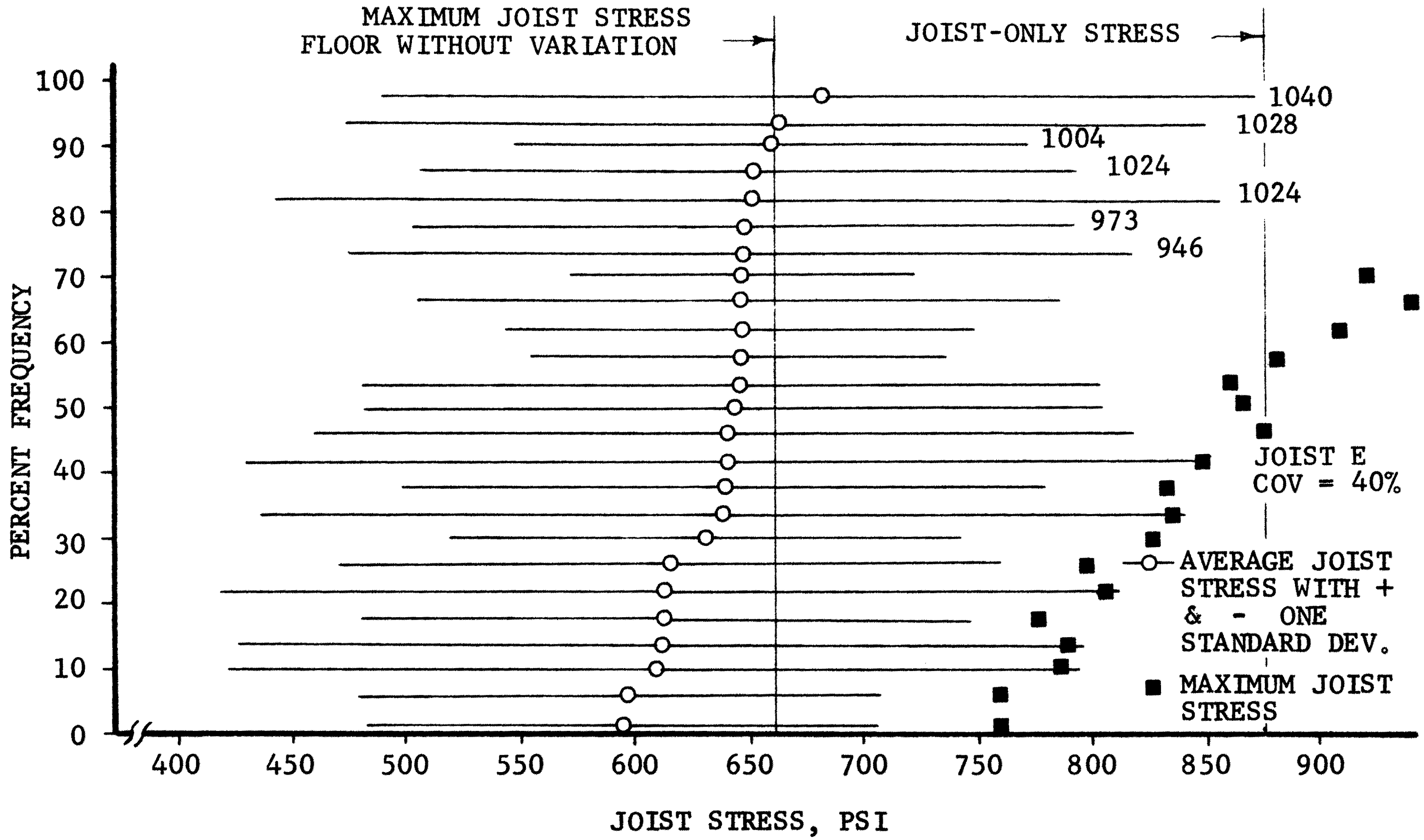


FIGURE A-6

CUMULATIVE AVERAGE JOIST STRESS DISTRIBUTION - SIMULATION 3

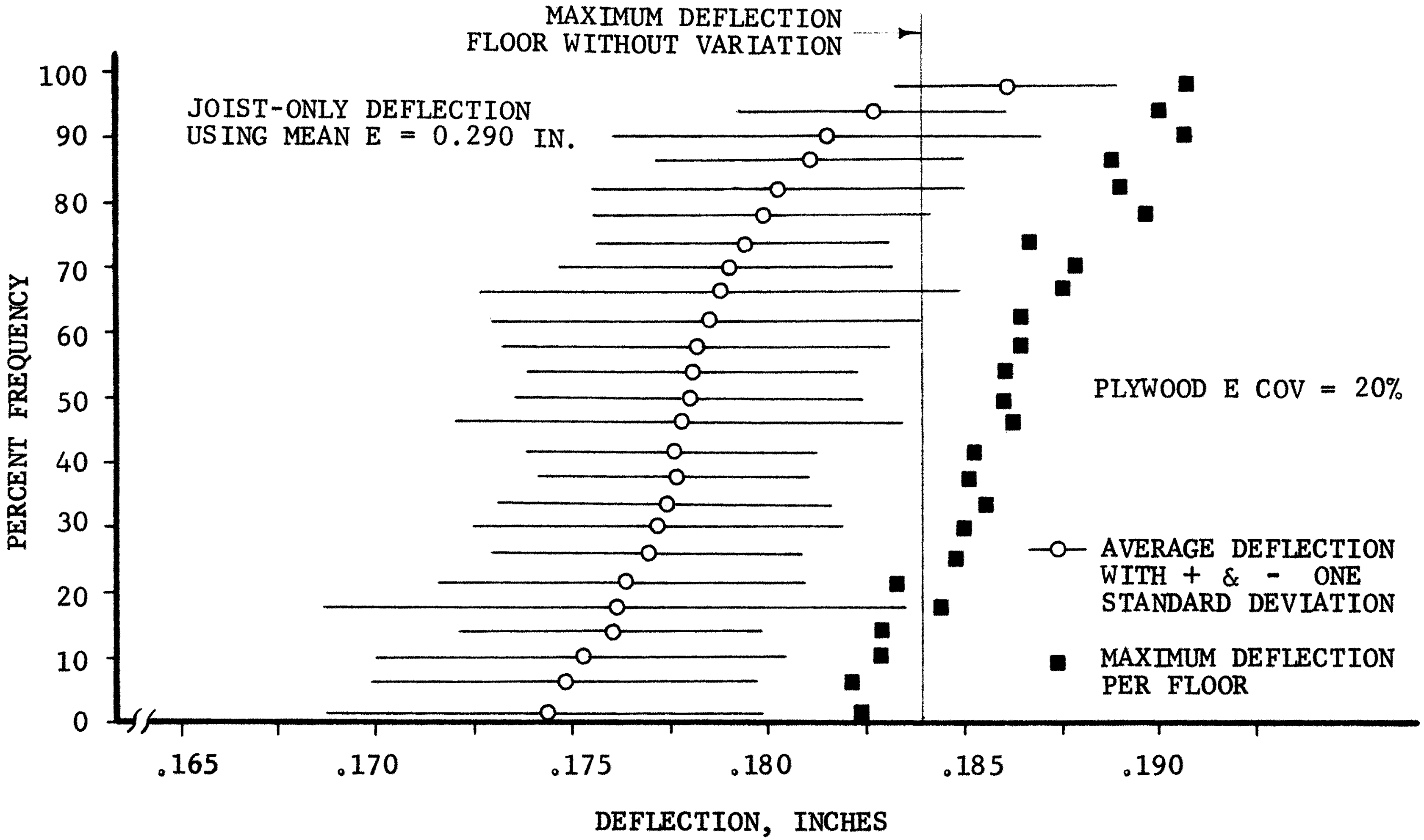


FIGURE A-7

CUMULATIVE AVERAGE DEFLECTION DISTRIBUTION - SIMULATION 4

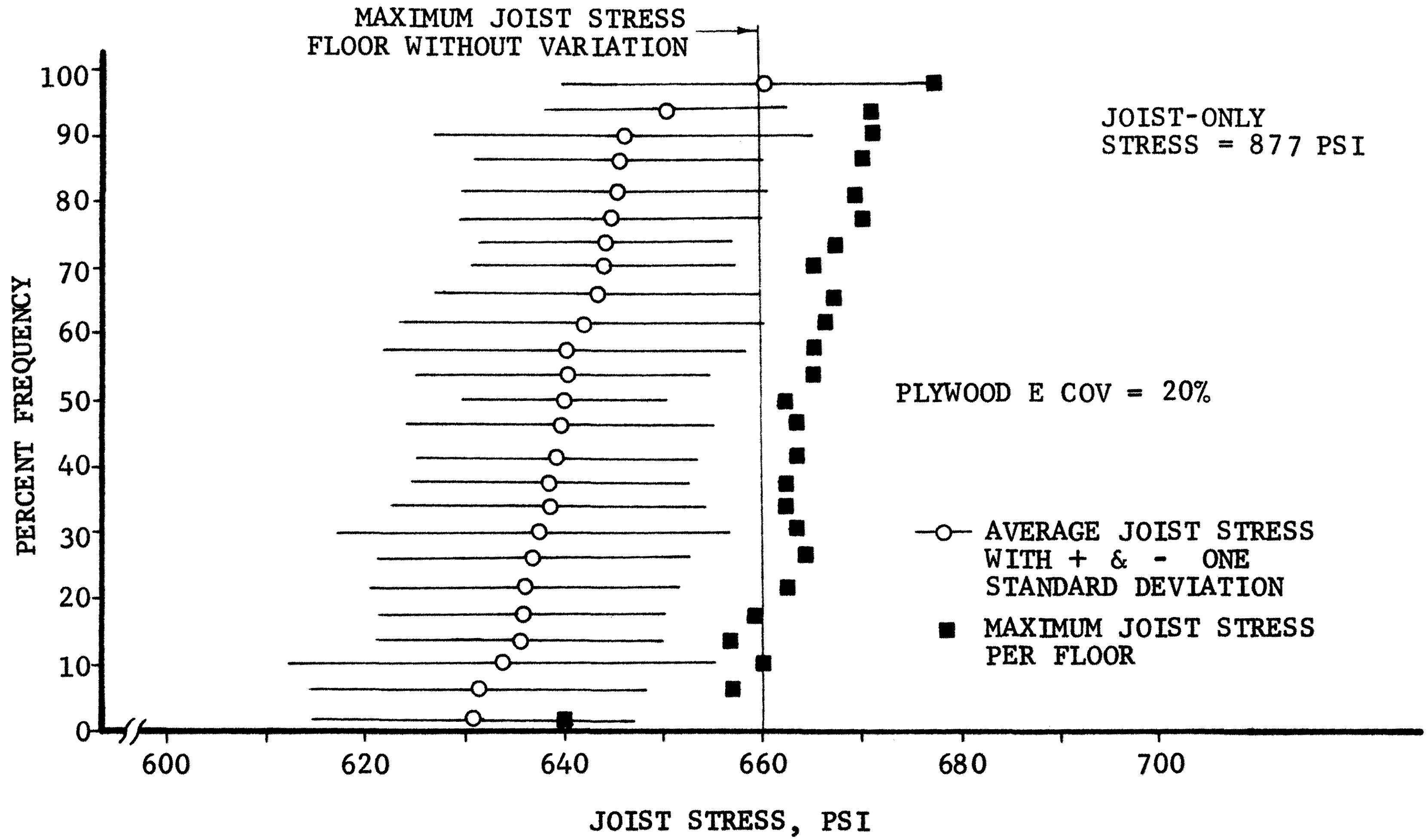


FIGURE A-8

CUMLATIVE AVERAGE JOIST STRESS DISTRIBUTION - SIMULATION 4

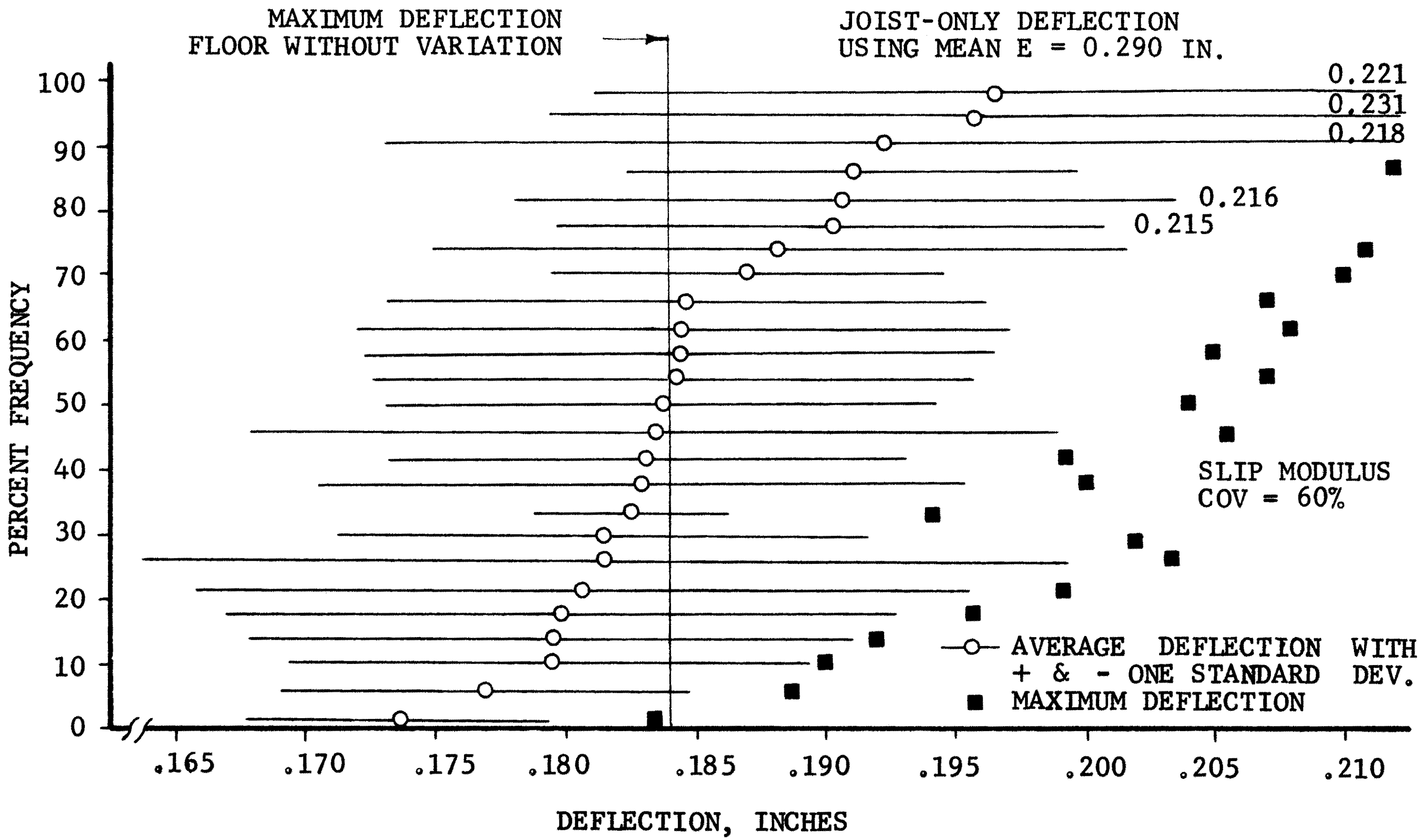


FIGURE A-9

CUMULATIVE AVERAGE DEFLECTION DISTRIBUTION - SIMULATION 5

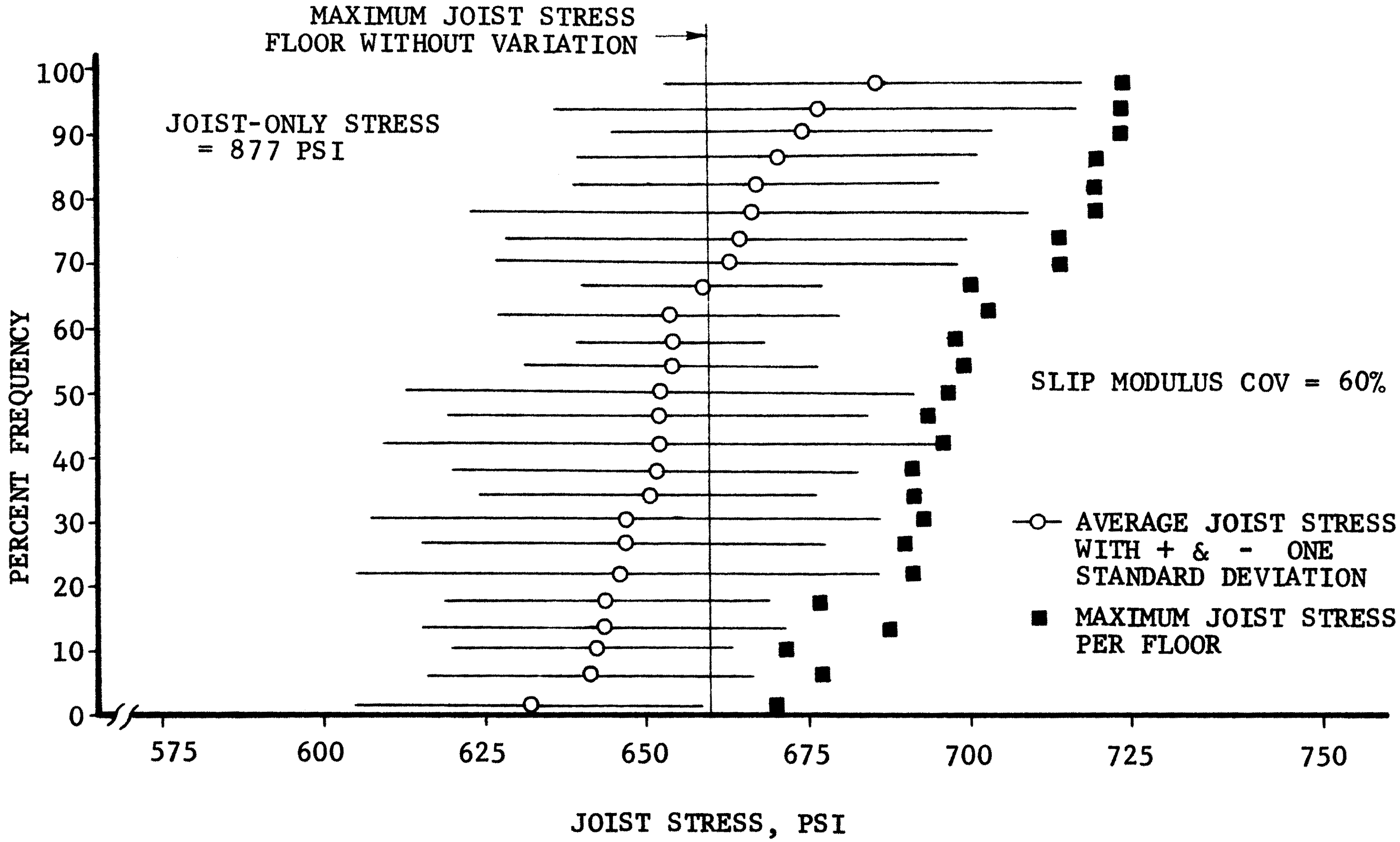


FIGURE A-10

CUMULATIVE AVERAGE JOIST STRESS DISTRIBUTION - SIMULATION 5

APPENDIX B SPECIFIED AND SAMPLE PROPERTY MEANS AND COV VALUES

The mean component values and component variabilities computed from the values assigned in the simulation studies will not be exactly equal to those specified because of the finite sample size involved.

This appendix presents in tabular form the statistical characteristics of the floors actually included in each simulation to aid in comparing the specified and the resulting values of both mean value and coefficient of variation. The specified values are also given in Tables 3.1, 4.1, 5.1 and 5.2, and shown in parenthesis in this Appendix.

APPENDIX B

Resultant Mean Values and COV

Simulation Number	Mean Joist E PSI x 10^{+6}	COV Joist E Percent	Mean Plywood E*, PSI x 10^{+6}	COV Plywood E, Percent	Mean Slip Modulus lbs/in.	COV Slip Modulus Percent
1	1.780 (1.80)	9.46 (10)				
2	1.761 (1.80)	19.03 (20)				
3	1.743 (1.80)	39.04 (40)				
4			1.330 ∥ (1.360) 0.517 ⊥ (0.529)	18.42 (20)		
5					28,200 (30,000)	58.72 (60)
6	1.798 (1.80)	19.22 (20)	1.361 ∥ (1.366) 0.529 ⊥ (0.529	9.09 (10)	30,400 (30,000)	39.62 (40)
7	1.793 (1.80)	19.24 (20)				
8			1.366 ∥ (1.361) 0.532 ⊥ (0.529)	18.67 (20)		
9					32,200 (30,000)	60.10 (60)
10	1.794 (1.80)	19.32 (20)				
11	1.763 (1.80)	20.03 (20)	1.387 ∥ (1.361) 0.540 ⊥ (0.529)	8.65 (10)	30,200 (30,000)	40.64 (40)

APPENDIX B Continued

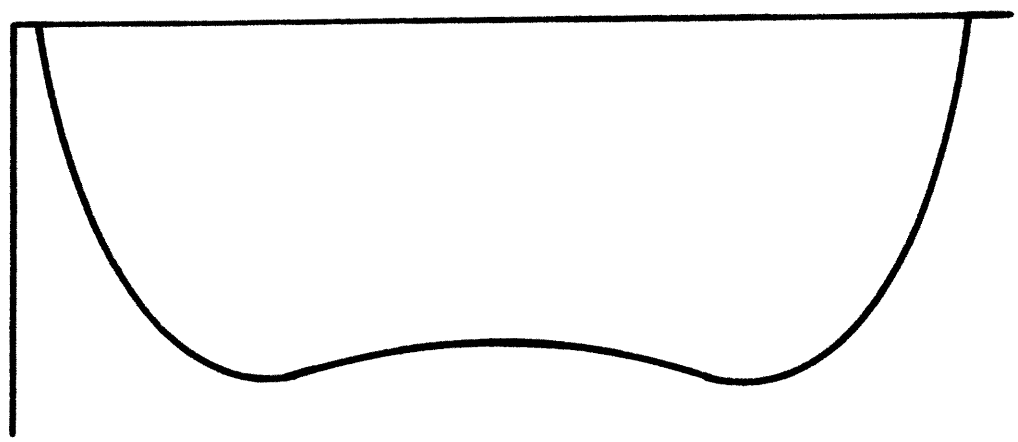
Simulation Number	Mean Joist E PSI x 10^{+6}	COV Joist E Percent	Mean Plywood E*, PSI x 10^{+6}	COV Plywood E, Percent	Mean Slip Modulus lbs/in.	COV Slip Modulus Percent
12	1.597 (1.60)	19.42 (20)				
13	1.599 (1.60)	19.08 (20)	0.771 ⊥⊥ (0.762) 0.076 ⊥ (0.074)	18.32 (20)	17,500 (18,000)	38.72 (40)
14	1.613 (1.60)	19.11 (20)	1.286 ⊥⊥ (1.310) 0.099 ⊥ (0.101)	19.42 (20)	27,900 (30,000)	59.93 (60)
15			1.322 B.M. ⊥⊥ (1.385) 0.376 B.M. ⊥ (0.394) 1.392 W.M. ⊥⊥ (1.385) 0.396 W.M. ⊥ (0.394)	8.62 B.M. (11) 11.27 W.M. (13)		
16	1.562 B.M. (1.60) 1.620 W.M. (1.60)	6.31 B.M. (9) 15.77W.M. (18)	1.311 B.M. ⊥⊥ (1.385) 0.373 B.M. ⊥ (0.394) 1.385 W.M. ⊥⊥ (1.385) 0.394 W.M. ⊥ (0.394)	8.44 B.M. (11) 11.32 W.M. (13)		
17	1.540 B.M. (1.60) 1.610 W.M. (1.60)	7.75B.M. (9) 18.20W.M. (18)	1.367 B.M. ⊥⊥ (1.385) 0.389 B.M. ⊥ (0.394) 1.396 W.M. ⊥⊥ (1.385) 0.397 W.M. ⊥ (0.394)	9.81 B.M. (11) 12.82 W.M. (13)	22,800 (22,700)	60.40 (60)
18	1.510 W.M. (1.60)	17.51W.M. (18)				

APPENDIX B Continued

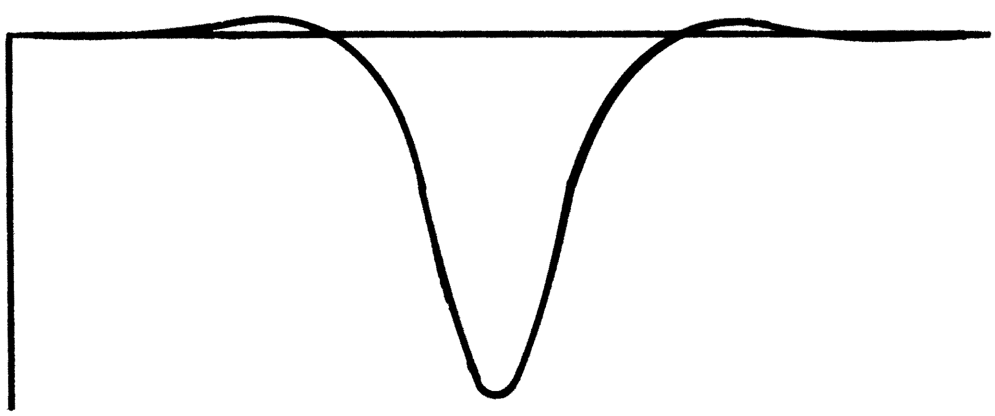
Simulation Number	Mean Joist E PSI x 10^{+6}	COV Joist E Percent	Mean Plywood E*, PSI x 10^{+6}	COV Plywood E, Percent	Mean Slip Modulus lbs/in.	COV Slip Modulus Percent
19	1.512 B.M. (1.60)	11.94 B.M. (9)				
20	1.547 B.M. (1.60) 1.600 W.M. (1.60)	10.81 B.M. (9) 17.59 W.M. (18)				
21	1.637 (1.60)	18.94 (20)	0.762 ⊥⊥ (0.762) 0.074 ⊥ (0.074)	17.51 (20)	34,100 (35,000)	40.37 (40)
22			0.239* (.250)	38.83* (40)		
23	1.493 B.M. (1.60) 1.601 W.M. (1.60)	6.46 B.M. (9) 18.02 W.M. (18)	1.435 B.M. ⊥⊥ (1.440) 0.314 B.M. ⊥ (0.315) 1.440 W.M. ⊥⊥ (1.440) 0.315 W.M. ⊥ (0.315)	9.59 B.M. (11) 13.11 W.M. (13)	35,600 (35,000)	59.61 (60)
24	1.516 B.M. (1.60) 1.601 W.M. (1.60)	10.70 B.M. (9) 17.44 W.M. (18)	1.385 B.M. ⊥⊥ (1.440) 0.303 B.M. ⊥ (0.315) 1.444 W.M. ⊥⊥ (1.440) 0.316 W.M. ⊥ (0.315)	10.47 B.M. (11) 13.04 W.M. (13)	35,500 (35,000)	59.87 (60)

B.M. = Between Mill Variation
W.M. = Within Mill Variation
* = Reference to Particle Board
⊥⊥ = Parallel E Value
⊥ = Perpendicular E Value
+ = Using Gross Untransformed Section
( ) = Specified Value

APPENDIX C FLOOR DEFLECTION PROFILES FOR UNIFORM AND CONCENTRATED LOADS*



UNIFORM LOAD, NO VARIABILITY



CONCENTRATED LOAD, NO VARIABILITY

* TYPICAL DEFLECTION PROFILES ALONG THE JOIST CENTERLINES FOR FLOORS WITH NO MATERIAL VARIABILITY AND THE CHARACTERISTICS GIVEN IN FIG. 3.1

APPENDIX D FIT OF SELECTED RESULTS TO A NORMAL DISTRIBUTION

The maximum floor response values from Simulations 2, 3 and 22 are shown in this appendix plotted on normal probability paper to give an indication of the accuracy of assuming that the response of simulated floor systems are normally distributed. The three simulations having their response displayed in this appendix were chosen to correspond to the simulation giving the approximate average, the highest and the lowest error of the estimate value for maximum joist deflection in Table 6.3. For plotting these curves the first point was assumed at the middle of the 0 to 4 percent interval and subsequent points were plotted at intervals of 4 percent. This was done to minimize the unrealistic distortions which can result at near the ends of such probability plots with small sample sizes.

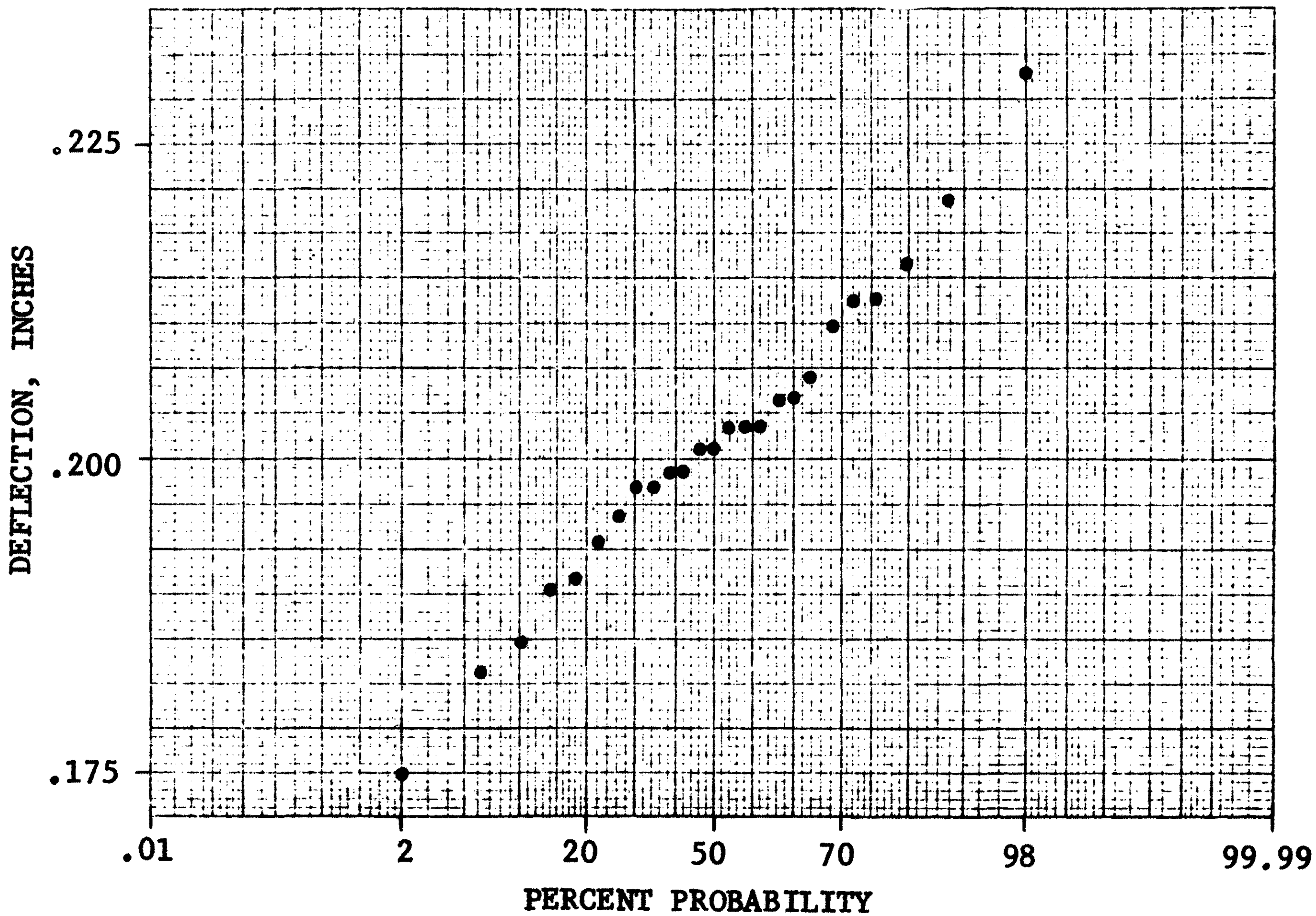


FIGURE D-1

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 2

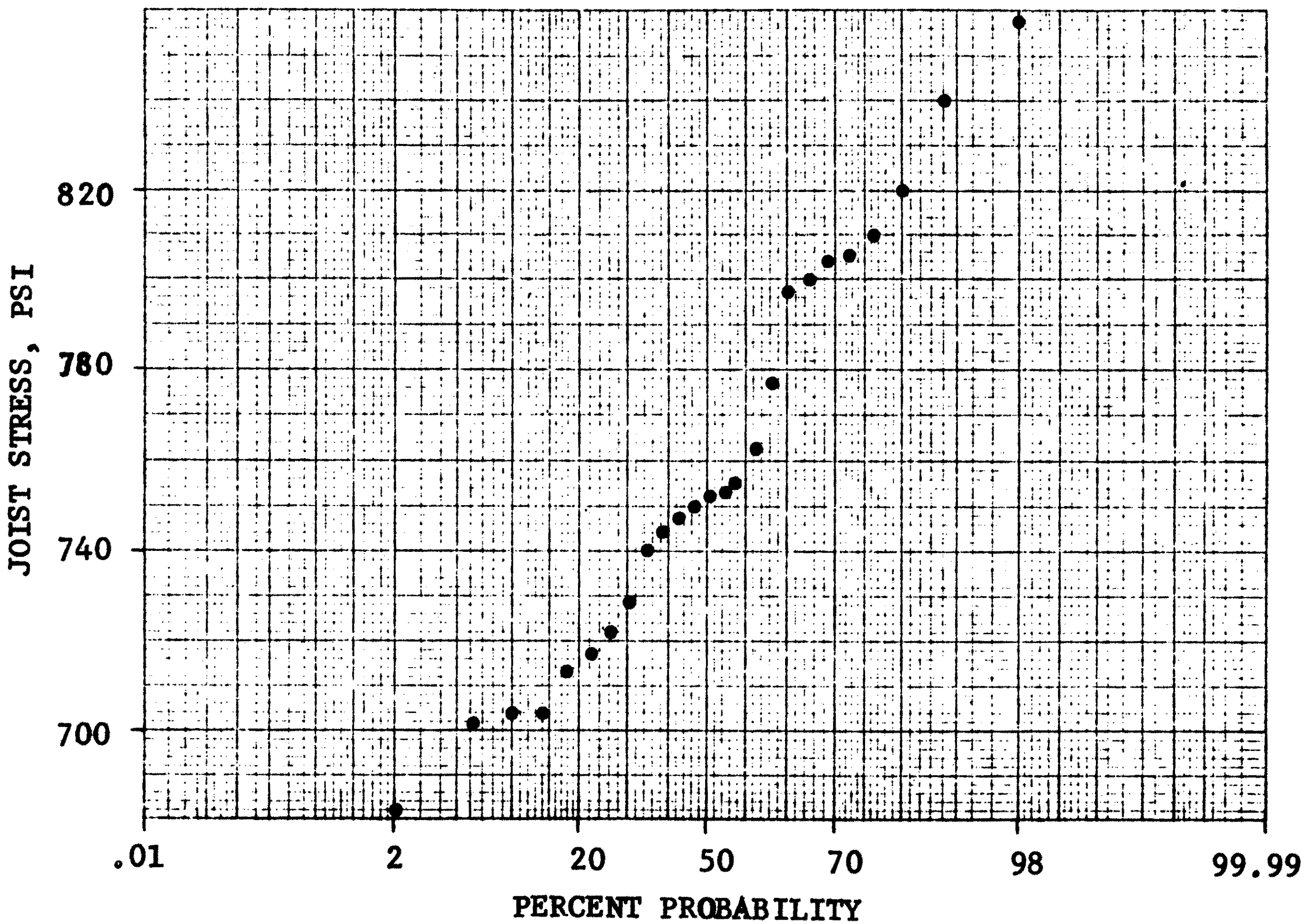


FIGURE D-2
CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 2

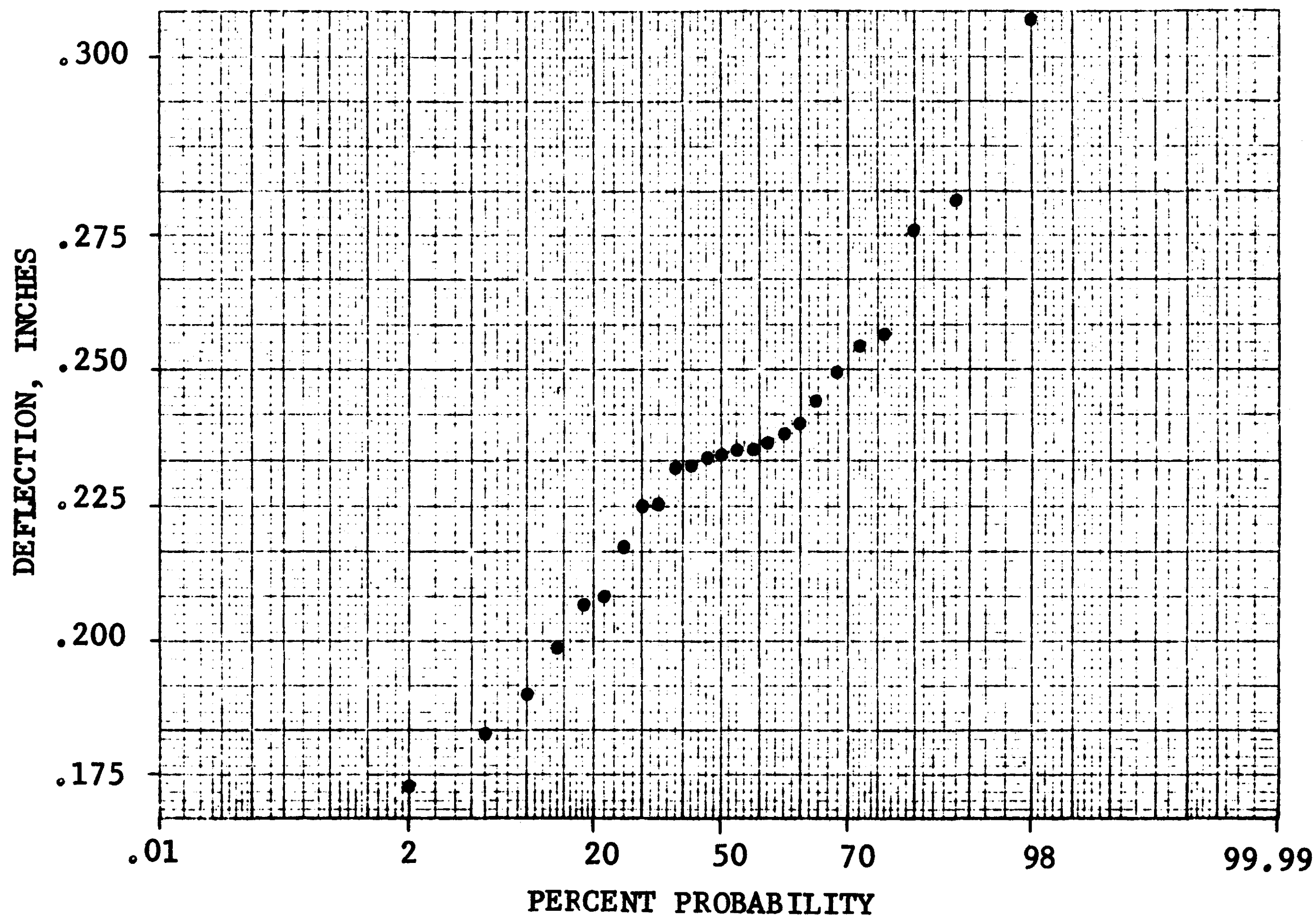


FIGURE D-3

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 3

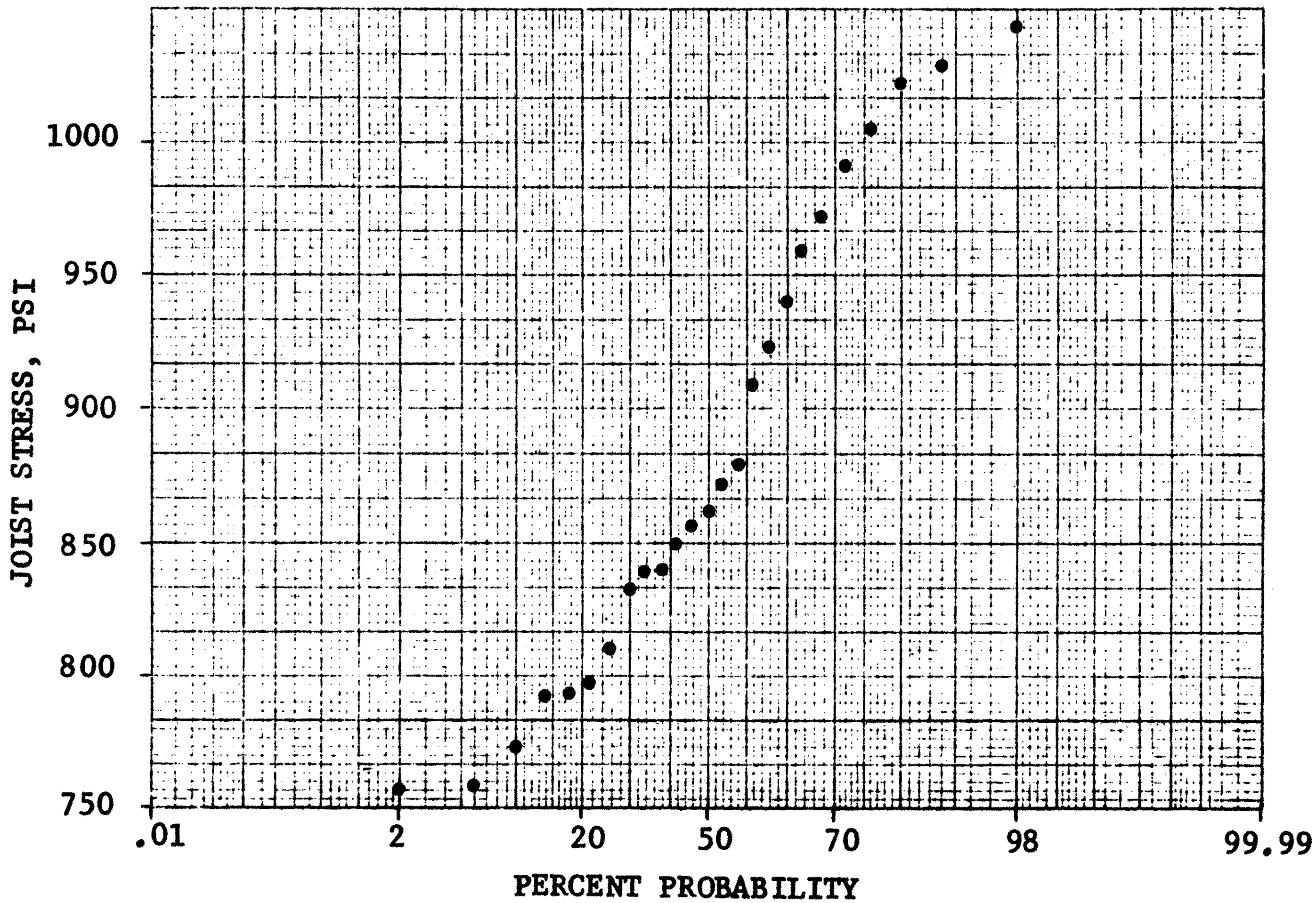


FIGURE D-4

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 3

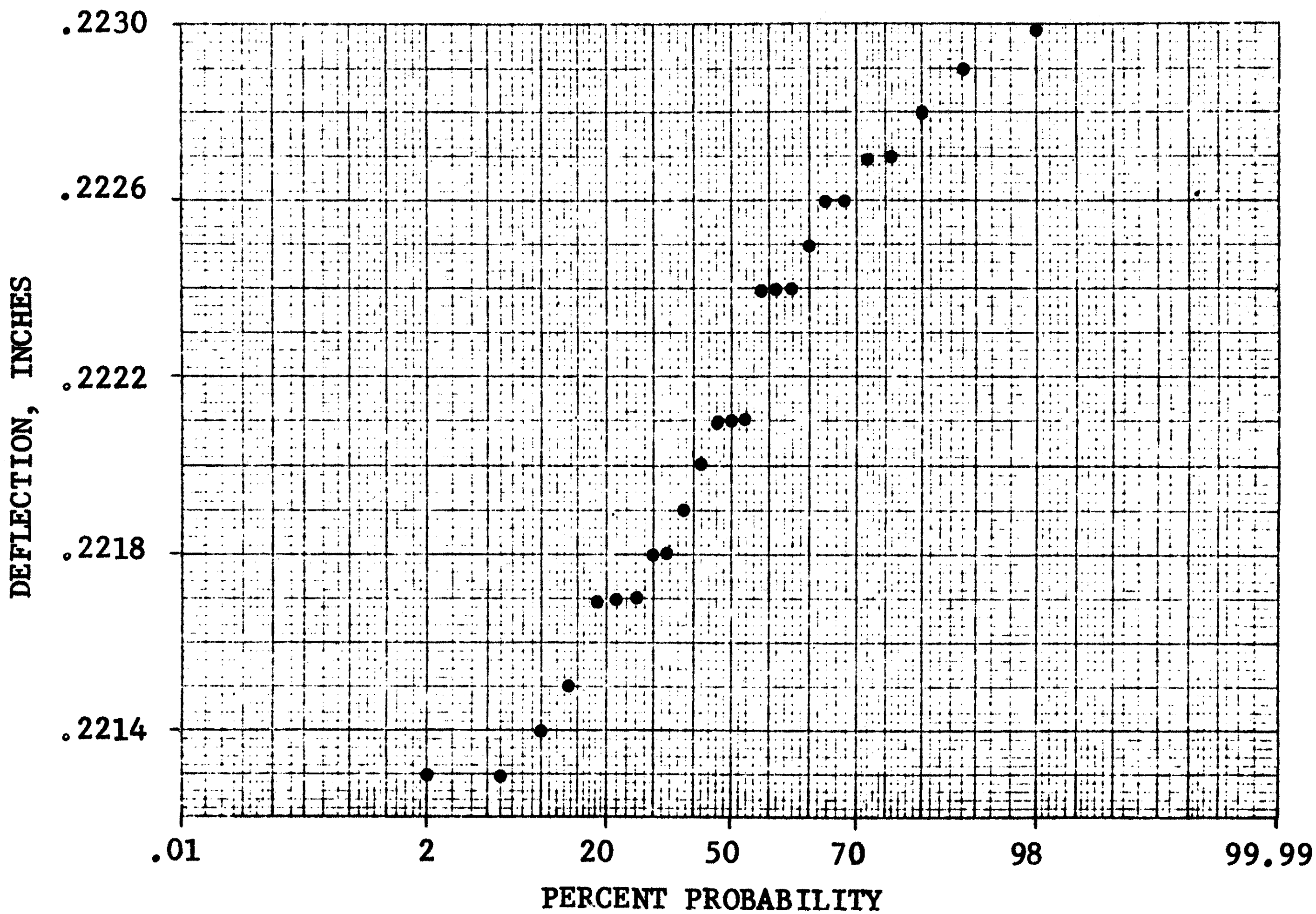


FIGURE D-5

CUMULATIVE MAXIMUM DEFLECTION DISTRIBUTION - SIMULATION 22

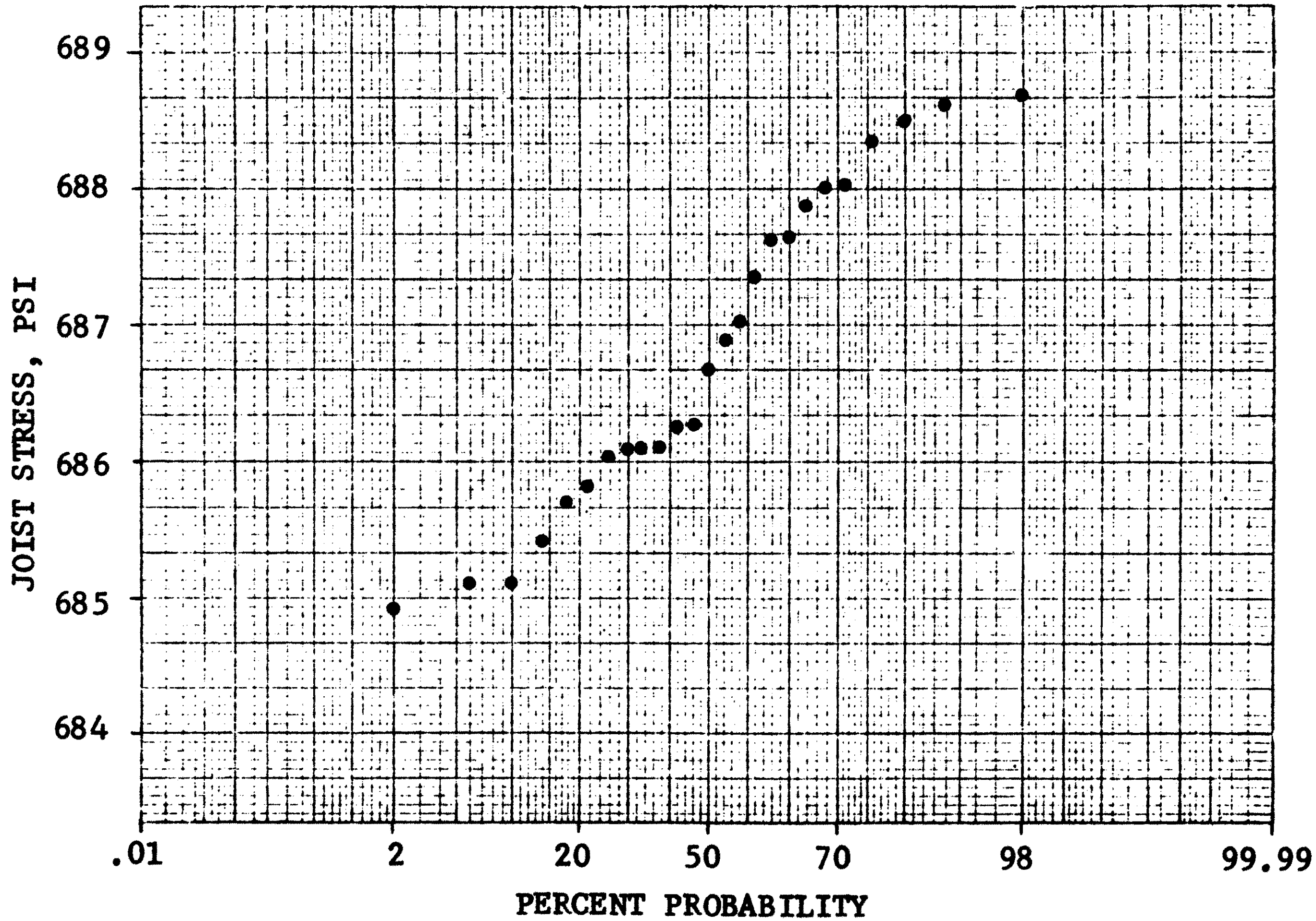


FIGURE D-6

CUMULATIVE MAXIMUM JOIST STRESS DISTRIBUTION - SIMULATION 22

APPENDIX E DETAILED RESPONSE OF SELECTED FLOORS

Typical floor deflections and joist stresses for one floor from each of the first six simulations are presented in this appendix. Joist only response values as well as response values for the floor system with no component stiffness variability are also provided so that comparisons can be made between the simulated floor response and the two idealized cases.

The figures of this appendix show how material variability can affect the entire floor system and the advantages of considering the floor system to act as a unit.

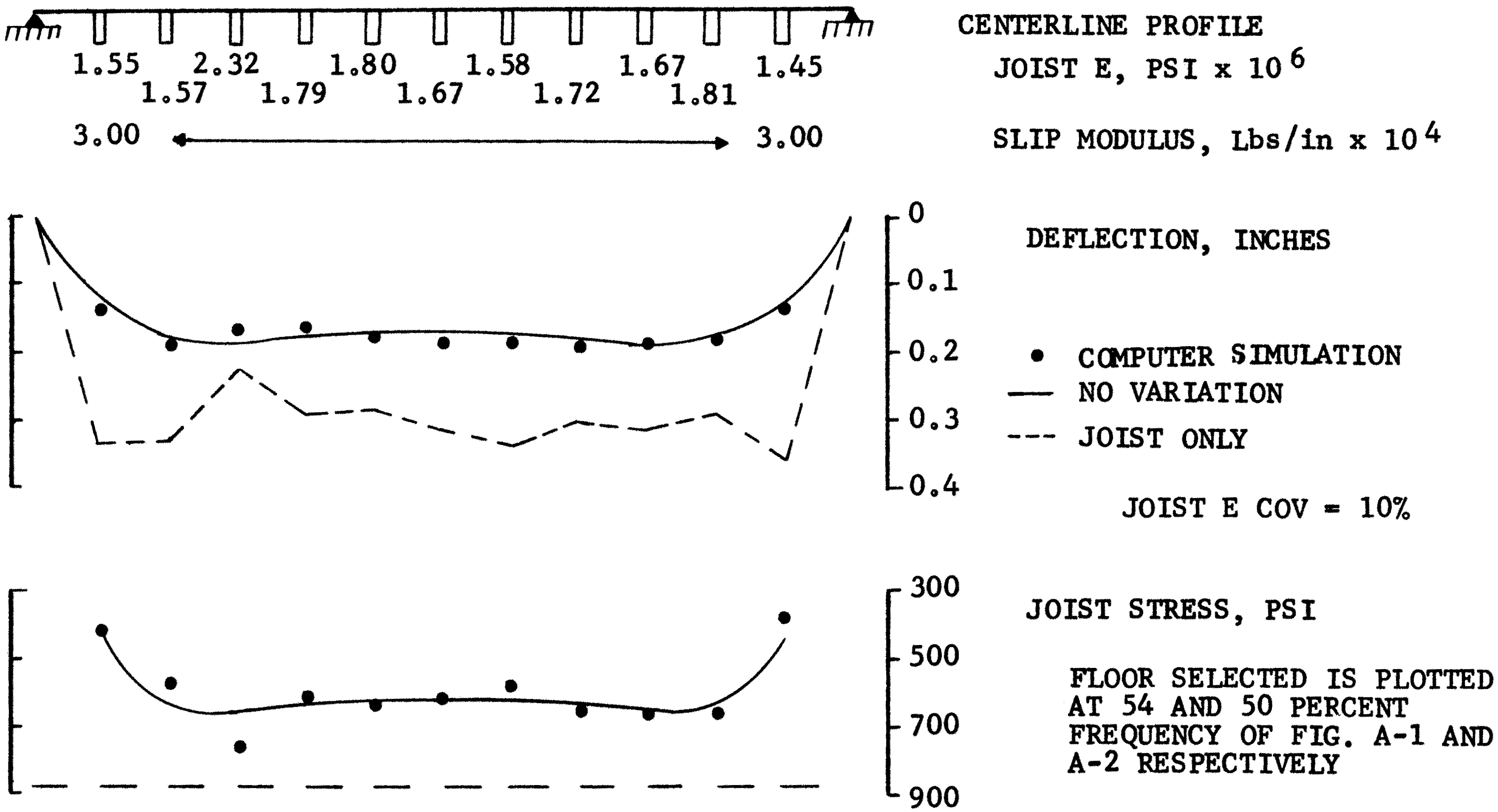


FIGURE E-1 SIMULATION NUMBER 1

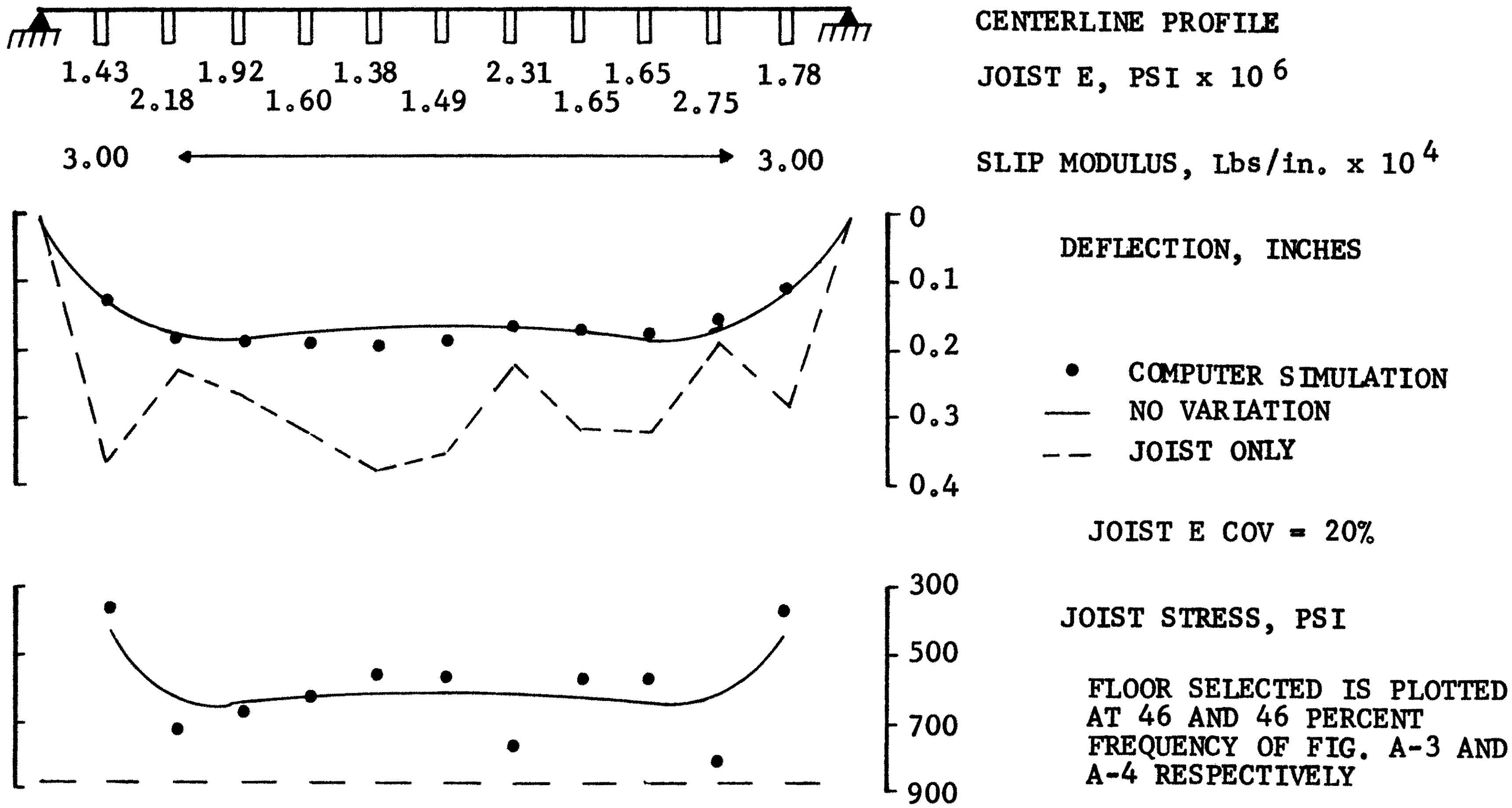
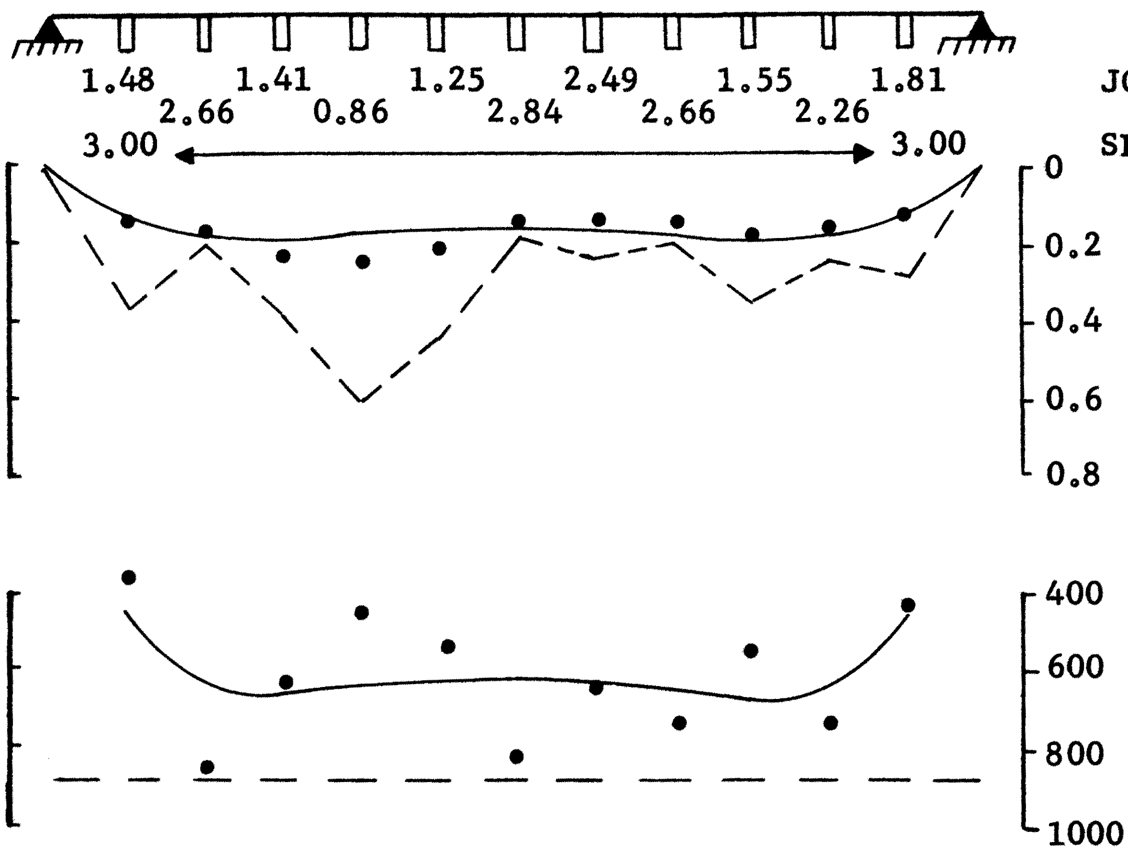


FIGURE E-2 SIMULATION NUMBER 2



CENTERLINE PROFILE

JOIST E, PSI x 10^6

SLIP MODULUS, Lbs/in. x 10^4

DEFLECTION, INCHES

• COMPUTER SIMULATION
—— NO VARIATION
- - - JOIST ONLY

JOIST E COV = 40%

JOIST STRESS, PSI

FLOOR SELECTED IS PLOTTED AT 42 AND 46 PERCENT FREQUENCY OF FIG. A-5 AND A-6 RESPECTIVELY

FIGURE E-3 SIMULATION NUMBER 3

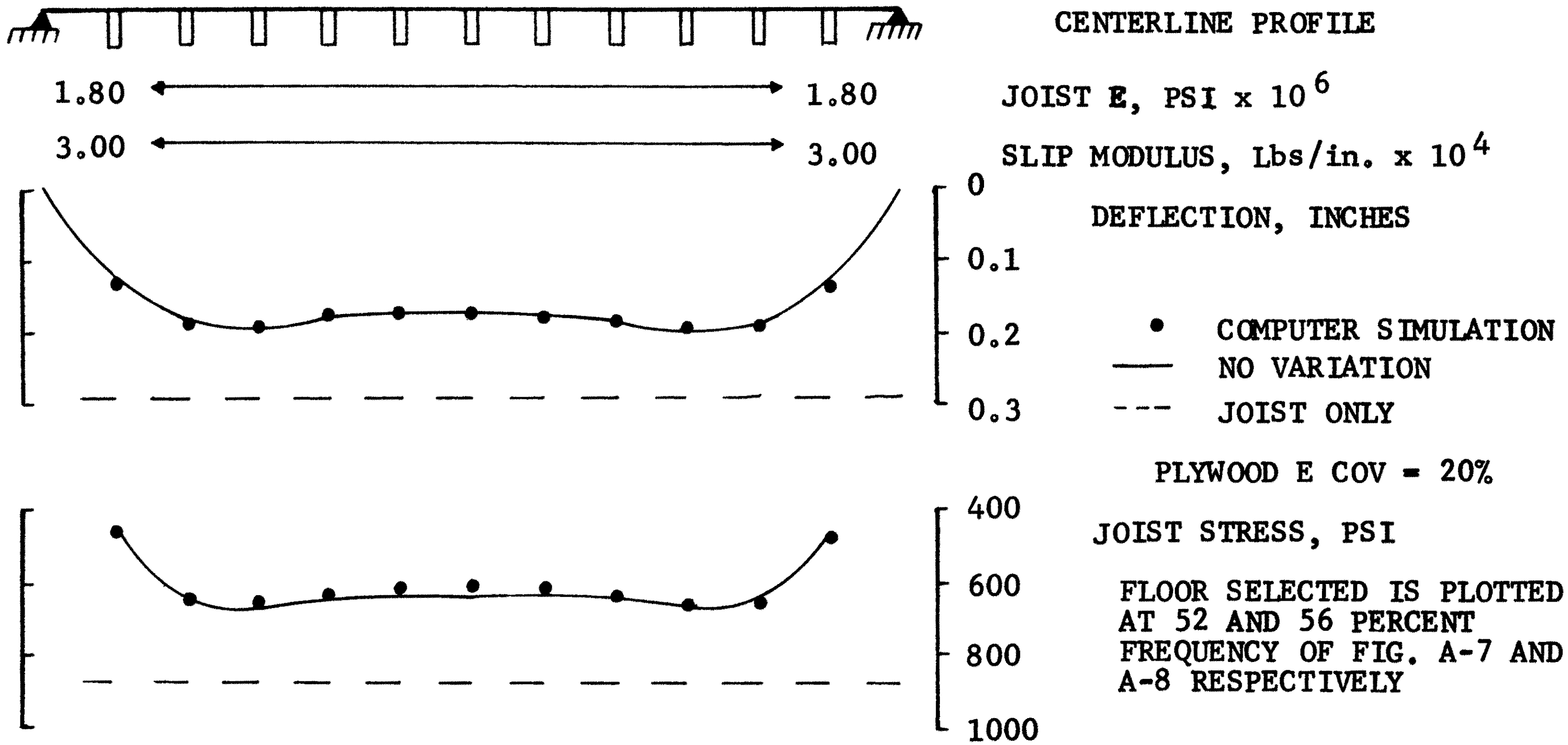


FIGURE E-4 SIMULATION NUMBER 4

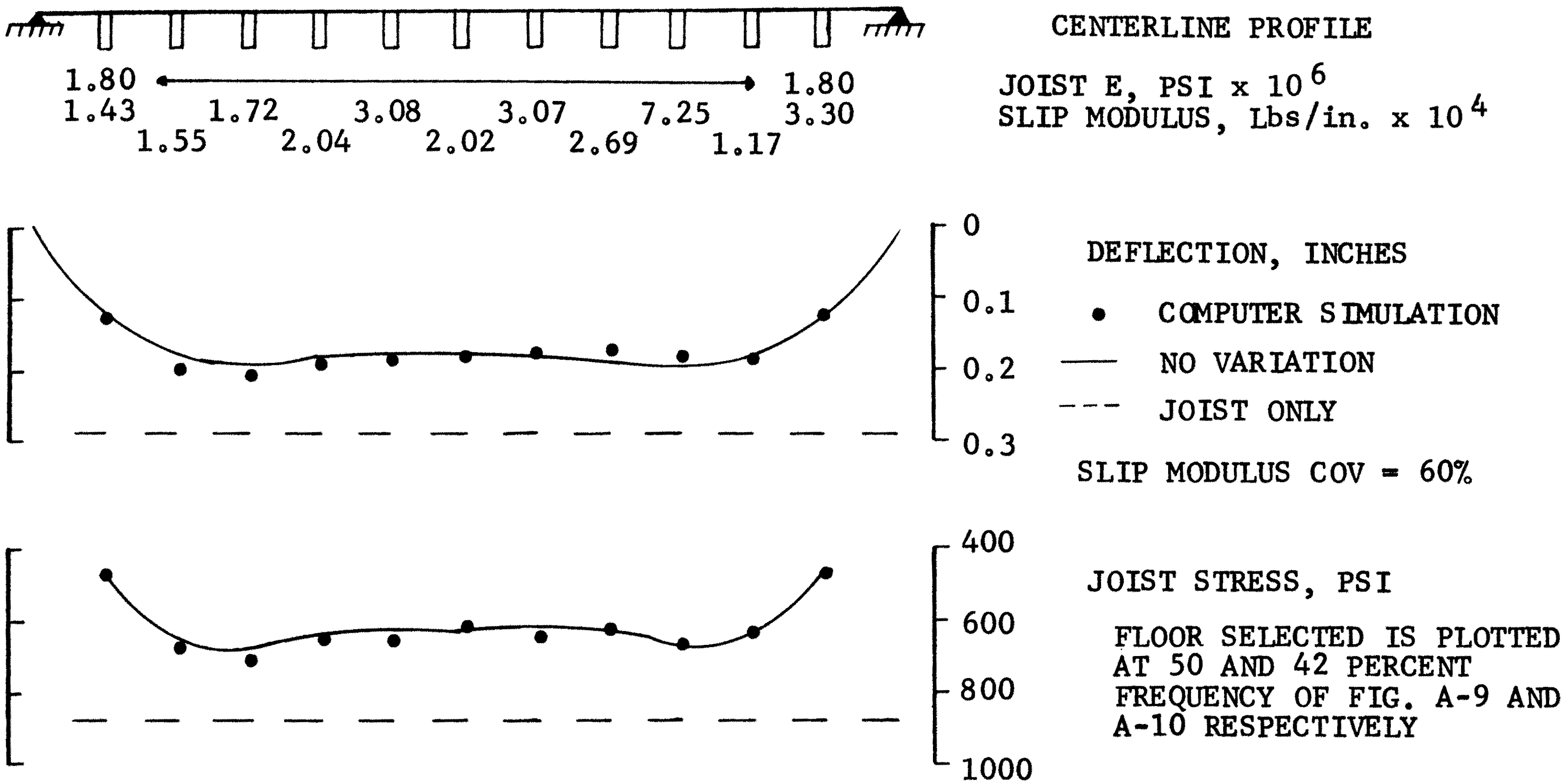


FIGURE E-5 SIMULATION NUMBER 5

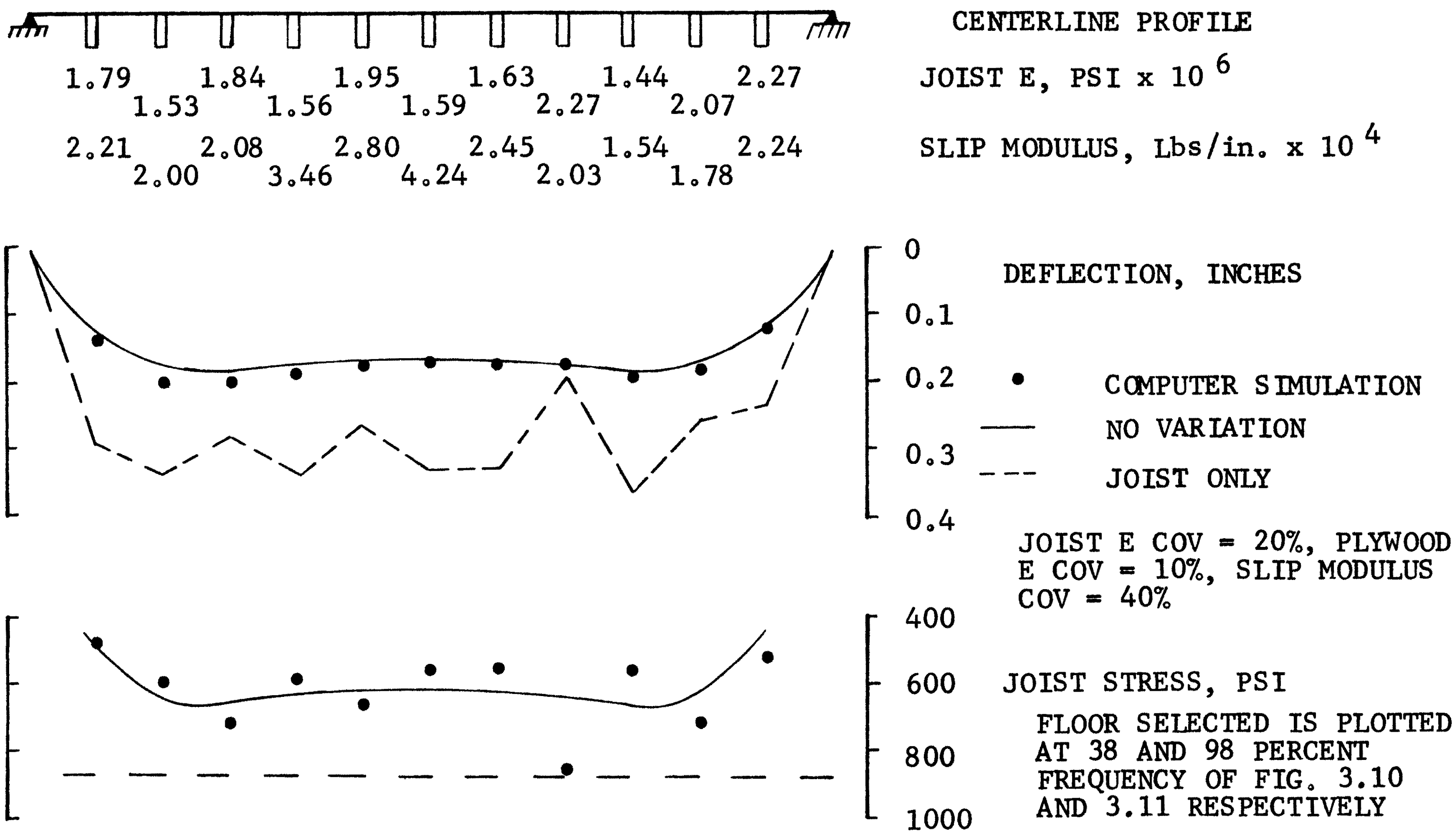


FIGURE E-6 SIMULATION NUMBER 6

APPENDIX F VARIATION OF PLYWOOD STRESSES, SIMULATION 8

To show that the plywood stresses of all the simulations conducted in this study are small (in the T-beam direction) the cumulative maximum compressive stress for both the top and bottom of the plywood are displayed for one simulation.

Simulation 6 was chosen for this appendix because it had the highest mean maximum plywood stresses of all of the simulations involved in the study.

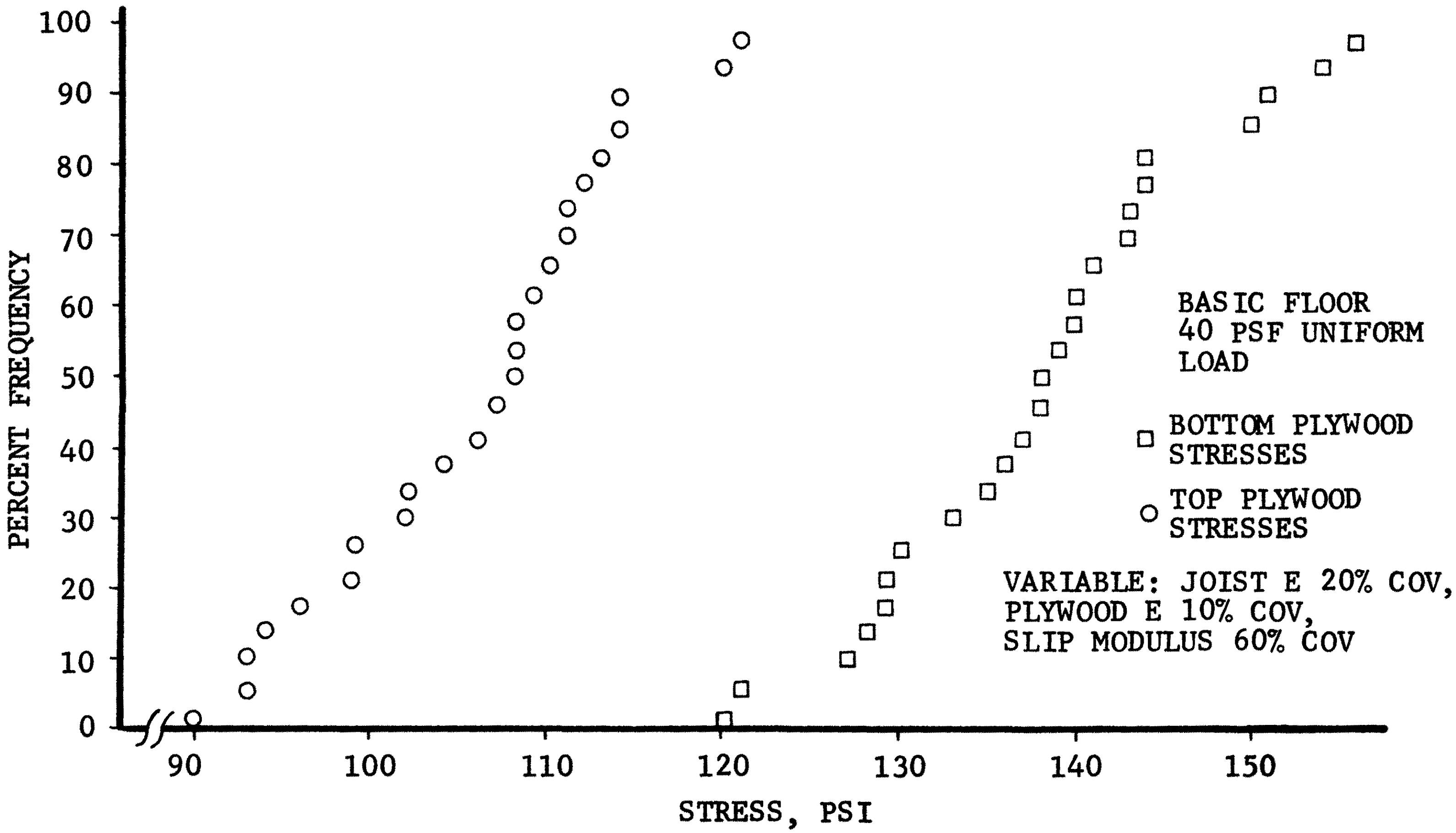


FIGURE F-1

CUMULATIVE MAXIMUM COMPRESSIVE PLYWOOD STRESSES - SIMULATION 6