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Factors Affecting Strength and Stability of Wood Cribbing: Height, Configuration, and Horizontal Displacement

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

deg	degree	in/min	inch per minute
ft	foot	lb	pound
in	inch	pct	percent
in^2	square inch	st/yr	short ton per year

FACTORS AFFECTING STRENGTH AND STABILITY OF WOOD CRIBBING: HEIGHT, CONFIGURATION, AND HORIZONTAL DISPLACEMENT

By Thomas M. Barczak[1] and Carol L. Tasillo[2]

ABSTRACT

The Bureau of Mines is conducting research to optimize the capability of mine roof supports so that the selection and design of these supports are compatible with the conditions in which they are to be employed. This report describes a study that investigates three parameters influencing the load-carrying capability of wood crib supports: height, configuration, and horizontal displacement. Four crib heights, four parallelogram configurations, and three ratios of horizontal-to-vertical displacements were tested on full-scale wood crib supports in a mine roof simulator. Test results indicated a reduction in load-carrying capability for increases in crib height. Increasing the contact area by changing the intersecting angle between crib blocks to form parallelogram configurations provided a slight increase in load-carrying capability for the first 10 to 12 in of vertical convergence, after which the cribs became more unstable, resulting in significantly less load-carrying capability. Horizontal displacements did not appreciably affect the load-carrying capability of wood crib supports for the range of vertical displacements (less than 10 in) likely to be encountered underground. This report documents these tests and postulates some explanations of failure mechanics for the observed behavior.

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INTRODUCTION

Wood cribs are used extensively by the coal mining industry in a variety of applications to stabilize mine openings. For example, crib supports have become an essential part of gate road design and strata control for retreat longwall mining.[3] A typical, 1 million-st/yr, longwall producing mine in the Eastern United States may spend up to $0.25 million per year in the procurement and installation of crib supports.[4] As illustrated in figure 1, the Bureau of Mines is conducting research to evaluate the load-displacement characteristics of passive roof supports, such as wood cribbing, so that the selection and design of these supports are compatible with the conditions in which they are to be employed.

The load-carrying capabilities of wood crib supports are generally evaluated in response to vertical (roof-to-floor) convergence, but in application, crib supports may also be subjected to horizontal displacements. This is particularly true in longwall mining where a free face is exposed by the excavation, with face-to-waste strata movement promoted by abutment loading ahead of the face area. This study investigated the effect of horizontal displacements on wood crib stability by controlled biaxial displacement of full-scale wood crib supports in a mine roof simulator (MRS). The MRS, illustrated in figure 2, is a sophisticated active test frame uniquely capable of applying controlled vertical and

[3]Coal Age. Operators Try New Roof Support. V. 92, Mar. 1987, pp. 30-33.

[4]Private communication with coal operators.

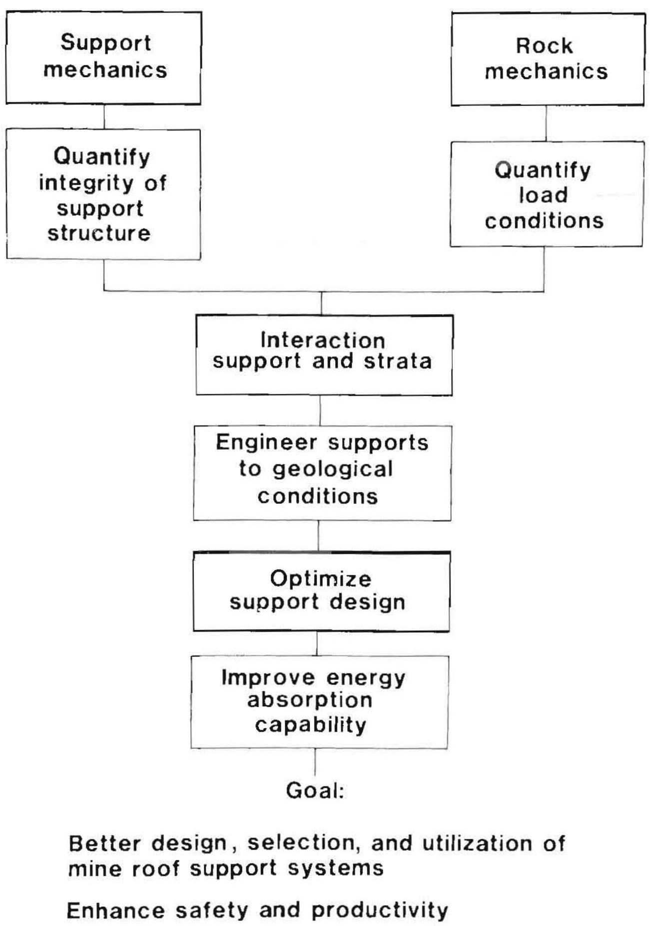


FIGURE 1.--Optimization of mine roof support systems.

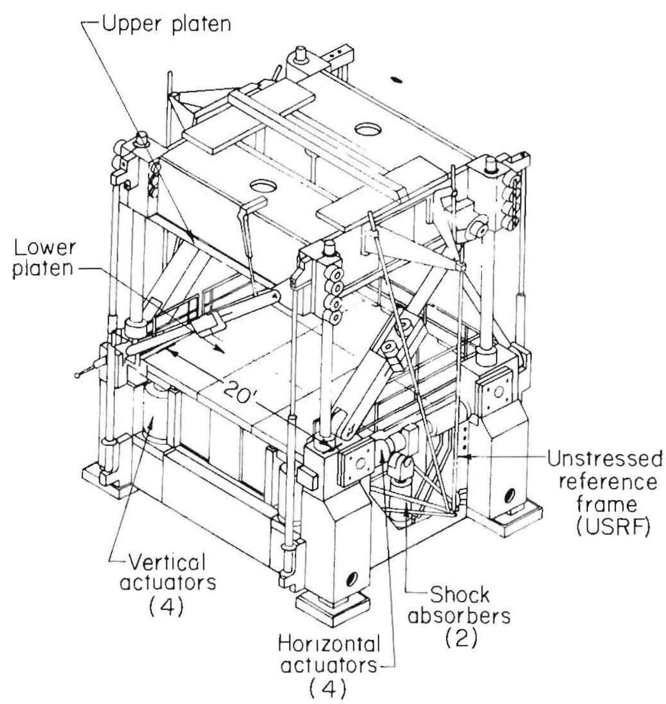


FIGURE 2.--Mine roof simulator.

horizontal displacements simultaneously to full-scale mine roof supports. A more detailed description of the MRS and its capabilities is provided in appendix A. Research on the effects of horizontal displacement on full-scale crib supports has not been attempted prior to this study.

The load-carrying capability of wood cribs is a function of the contact area between intersecting crib blocks. Wood cribs are generally constructed in square geometries, with two crib blocks per layer oriented in opposite directions in alternating layers such that the intersecting layers are at right angles to one another. Previous research on the load-carrying capability of wood crib supports has been limited to square geometries, as this is the standard construction employed by the mining industry. This investigation examined the effect of increasing the contact area by changing the geometry from square to parallelogram configurations, as shown in figure 3, by changing the intersecting angle between crib layers. The compressive strength and stability of several parallelogram configurations were evaluated by full-scale testing of wood crib structures in the MRS.

This research is considered to have a practical application in providing mine operators with more information about the behavior of wood cribs so that they can make better judgments regarding the utilization of such passive roof supports. It also provides fundamental information about the failure mechanics of crib support systems, which is essential to the development of improved designs. Previous research on wood crib performance has primarily been concerned with the material properties of wood, such as moisture content and grain orientation, with less attention given to structural parameters and failure mechanics.

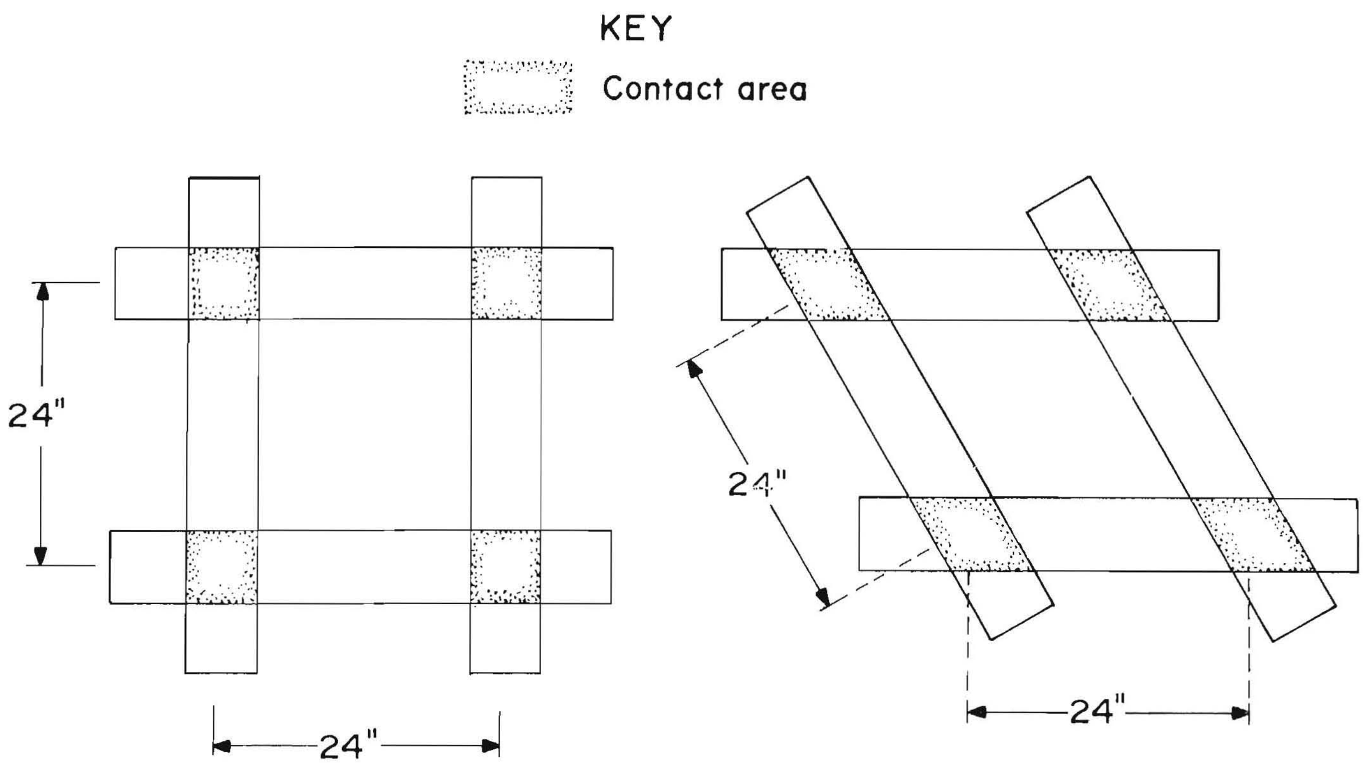


FIGURE 3.--Parallelogram crib configurations.

SCOPE OF INVESTIGATION

The scope of this investigation incuded three parameters affecting the strength and stability of wood crib supports: (1) height, (2) configuration, and (3) horizontal displacement. Tests were conducted by varying one parameter at a time while holding the other two constant. Four crib heights, four configurations, and three ratios of horizontal-to-vertical displacement were evaluated in this study. Three tests were performed on separate wood crib specimens for each of these parameter considerations, for a total of 120 tests. Test results were averaged for the three tests. Average test results are presented in the form of load-displacement plots (vertical force versus vertical convergence) to quantify and illustrate the effect of each parameter consideration.

A description of parameter considerations and rationale for selection follows.

Height

Crib heights of 50, 60, 80, and 110 in were investigated. These crib heights were chosen based on a 1986 census of 98 longwall mines at which extraction heights ranged from 42 to 150 in, with an average height of 75 in. The cribs were constructed with an even number of crib layers so that the top and bottom layers were always in opposing directions, to standardize the transfer and loading distribution through the crib. These construction practices resulted in an 80-in crib to represent the 75-in average seam height and a 50-in crib to represent the 42-in lower limit for longwall seams. The 110-in height was selected so that the three heights were incremented evenly and because cribs higher than 110 in typically are constructed of longer crib blocks. The 60-in height was selected after initial test results showed a change in crib behavior between 50 and 80 in.

Configuration

The contact area (A) between intersecting layers of a two-block-per-layer wood crib is a relationship of the width of the two crib blocks (W_1, W_2) and the intersecting angle (θ), illustrated in figure 4 and described in equation 1.

$$A = \frac{W_1 W_2}{\sin\theta} * 4 \qquad (1)$$

Configuration angles (angles of intersection between crib layers) of 90°, 75°, 60°, and 45° were selected, producing contact areas of 144, 149, 166, and 204 in^2, respectively. In order to standardize the moment of inertia during testing, the various geometry configurations maintined a constant pivot length of 24 in from center to center of the four points of contact about which the angle was rotated.

Horizontal displacements

Horizontal and vertical displacements were applied simultaneously during this test series. The tests were designed to produce displacement profiles that reach

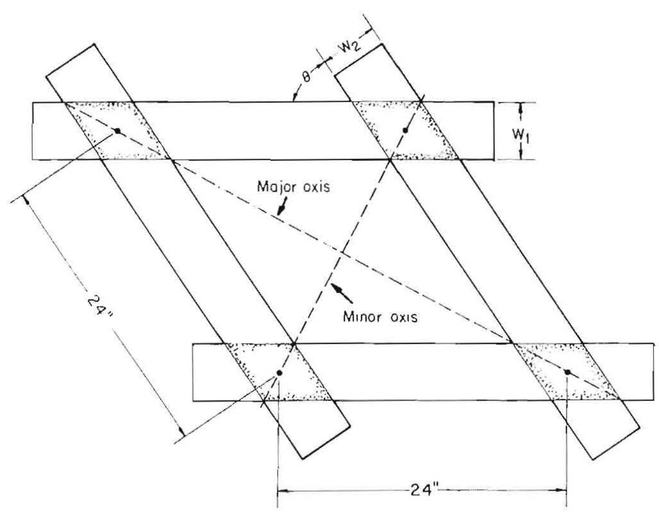


FIGURE 4.–Contact area relationships for parallelogram crib configurations.

maximum horizontal displacements of 0, 6, or 12 in at a maximum vertical displacement of 24 in. The maximum horizontal displacement of 12 in was selected because it was assumed that realistic horizontal displacement in a mine would not exceed 50 pct of the vertical convergence. Zero horizontal displacement represents a condition of pure vertical convergence, which is considered the control standard.

Parameters other than height, configuration, and convergence affect crib support behavior. Therefore, to study the effects of the three parameters selected for this investigation, an effort was made to keep all other influential parameters constant. A summary of other parameter considerations is provided below.

Wood type

All cribs were constructed using red oak crib blocks. Red oak is classified as a hardwood and is abundant in the local vicinity (Pennsylvania, West Virginia, Virginia) for mining applications.

Grain orientation

The compressive strength of wood can vary depending on the direction of the load, either radially or tangentially to the wood grain. An effort was made in the construction of the cribs to select blocks of the same basic grain orientation for individual layers to minimize differential compression on one side of the crib, which might promote localized buckling and overall crib instability.

Crib block dimensions

All cribs were constructed from 42-in-long, 5- by 6-in blocks.

Moisture content

No attempt was made to control the moisture content other than to maintain consistent overall conditions for wood storage. Since the wood was of the same type and cut at the same time, it is assumed the moisture content was fairly constant.

LOAD-DISPLACEMENT CHARACTERISTICS OF WOOD CRIBBING

A qualitative description of the load-displacement characteristics of wood cribbing is useful since data will be presented in this form. A typical load-displacement relationship of a wood crib is shown in figure 5. As seen from the figure, wood cribs are considered to be yieldable supports capable of withstanding several inches of vertical displacement before failing (reaching ultimate strength). It is also seen that the behavior of the crib changes as a function of displacement.

Three regions of behavior are defined: (1) elastic deformation, (2) plastic deformation, and (3) failure. The initial loading regime is characterized by elastic behavior where the load is a fairly linear function of applied displacement. This behavior is generally exhibited for the first 2 to 3 in of displacement. A significant reduction in stiffness then occurs, observed as an inflection in the load-displacement plot, with subsequent behavior characterized by large displacements with relatively little increase in support resistance (loading). This plastic deformation behavior generally occurs for several inches of displacement; 15 to 20 in is common for well-constructed

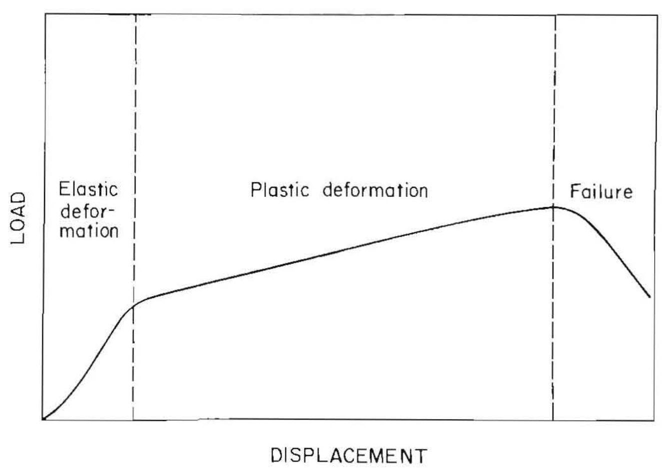


FIGURE 5.--Load-displacement relationship for wood crib supports.

cribs. Failure of the crib is defined to occur when the support reaches its maximum load; a reduction in load-carrying capability is associated with increased displacement after failure. Since failure of a wood crib generally occurs after 1 to 2 ft of displacement, it is not of primary concern in mining applications since this displacement is considered beyond the range of expected roof convergence.

TEST PROCEDURES

All tests were conducted under controlled conditions in the MRS. Cribs were constructed to the specified test height and geometry configuration and subjected to controlled displacement by the simulator.

Vertical displacement was applied at a rate of 0.5 in/min for the maximum simulator vertical stroke of 24 in. Horizontal displacements were provided by displacement of the lower MRS platen relative to the upper platen. Horizontal displacements and vertical displacements were applied simultaneously during the horizontal displacement test series. The displacement profile for biaxial displacements is illustrated in figure 6. This condition simulates horizontal displacement of the mine roof relative to the floor during vertical roof convergence. Top and bottom crib blocks were fitted into a fixture attached to the simulator platens to prevent slippage of the blocks when the horizontal displacement was applied.

Load-displacement plots were produced for each test to assess crib behavior. Observations were made of any changes in the profile (shape) of the crib structure during loading and failure. No attempt was made to measure any differential displacements, horizontally or vertically, within the crib structure during the tests. All force and displacement measurements were referenced to the MRS load platens.

TEST RESULTS AND INTERPRETATIONS

This section presents load-displacement relationships for each of the parameter considerations evaluated in this study. The results presented here are average test results from three tests on separate cribs. Individual test results are documented in appendix B. Test results were fairly consistent among individual test specimens, particularly during the first 5 to 10 in of vertical displacement. Most variation in the data occurred well into the plastic deformation range as the support was approaching failure.

HEIGHT CONSIDERATIONS

The influence of height on the load-carrying capability of wood cribs for each of the four configurations evaluated

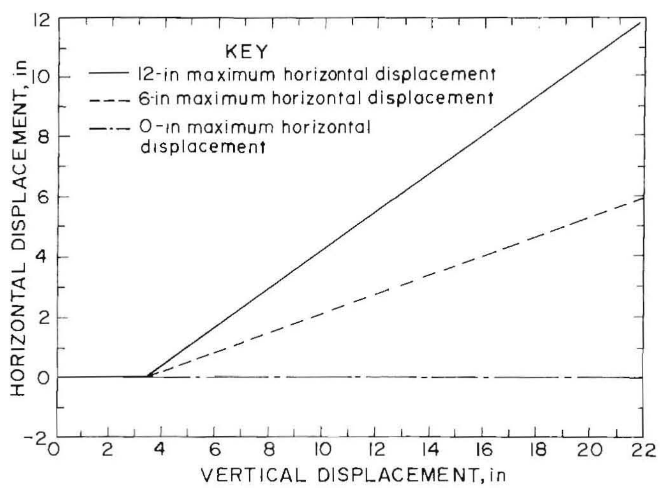


FIGURE 6.--Displacement profile for biaxial crib displacements.

is shown in figure 7. Figure 8 shows three graphs that illustrate the effect of height for each of the three horizontal displacements evaluated. The general behavior was a reduction in load-carrying capability for increases in height. This behavior was consistent for all configurations evaluated, while they remained stable, with and without horizontal displacement. As an example of the influence of crib height on wood crib performance, at 10 in of vertical convergence (no horizontal convergence), a 110-in-high conventional square crib had 35 pct less support resistance (vertical force) than a 50-in-high crib under the same conditions.

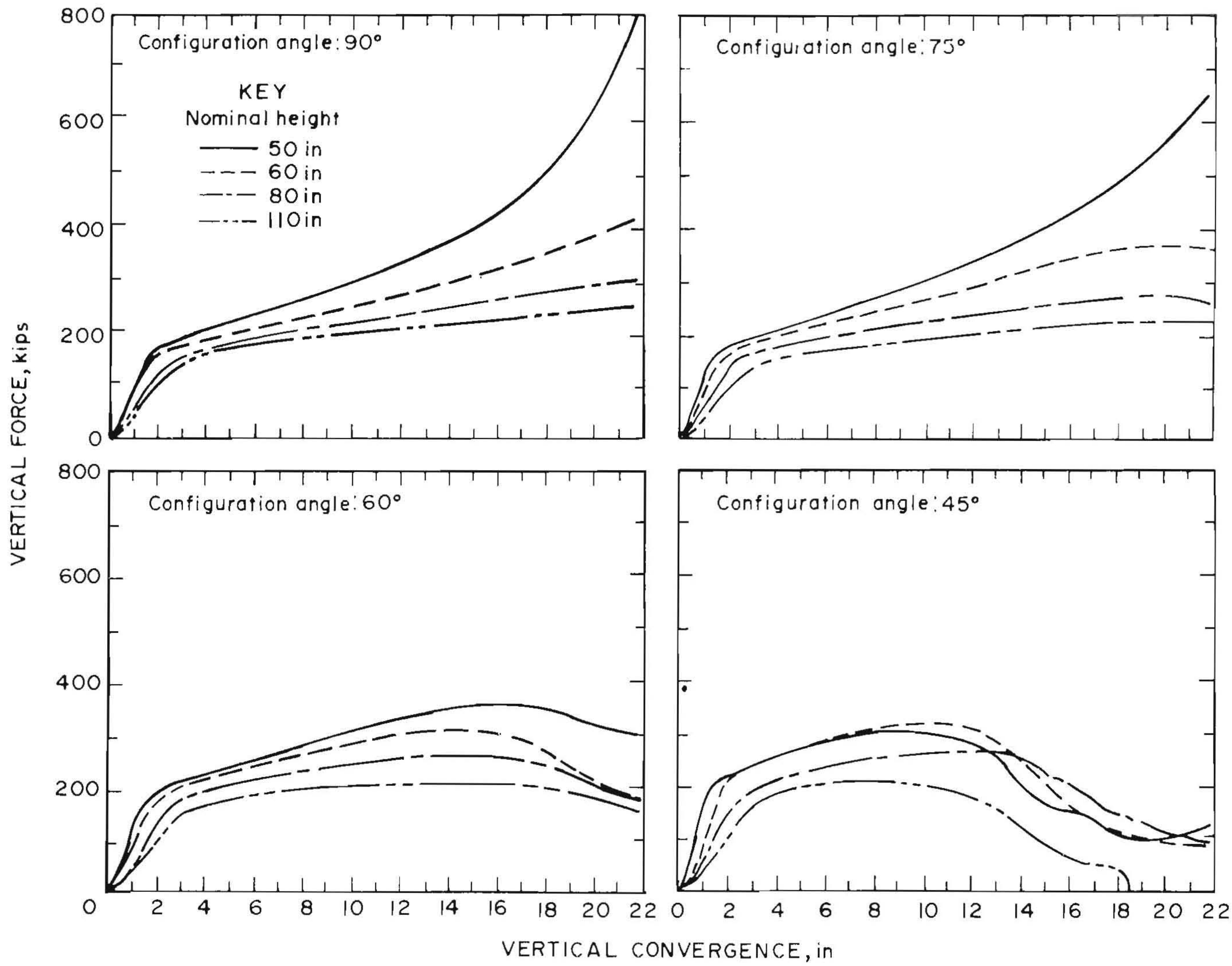


FIGURE 7.--Effect of crib height on load-carrying capability of various wood crib configurations.

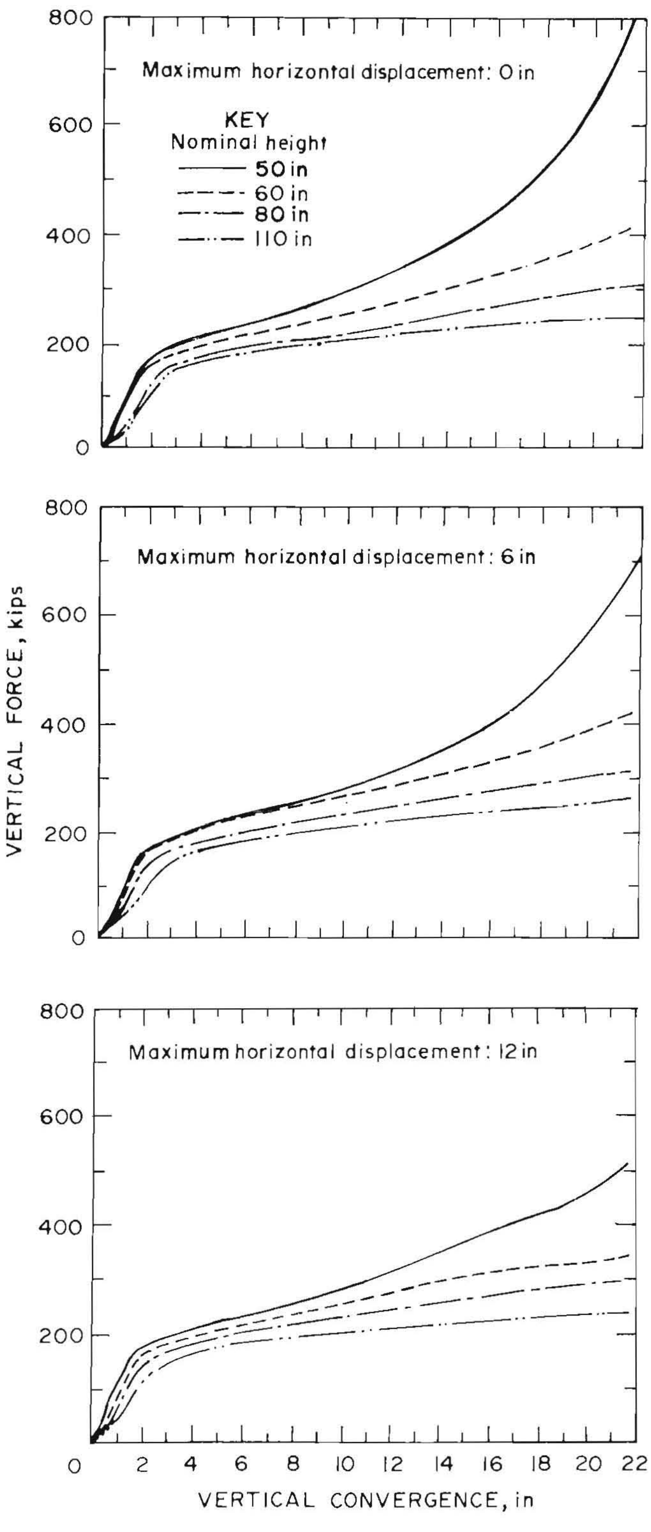


FIGURE 8.--Effect of crib height on wood crib supports subjected to biaxial displacements.

The influence of height on the load-displacement characteristics of wood crib supports is described as follows. A small increase in stiffness with reductions in height of the support structure was observed during the elastic deformation phase; this resulted in a slightly larger load reaction for shorter cribs than for taller cribs at the same displacement. A more significant change in behavior occurred during the plastic deformation phase. As the crib height was reduced, more of a nonlinear behavior was observed during the plastic deformation, showing a tendency of the crib to increase in stiffness with increasing vertical displacement, which significantly increased the maximum load-carrying capability of the crib.

CONFIGURATION CONSIDERATIONS

The effect of an increase in contact area on the load-carrying capability of wood cribs by decreasing the intersecting angle between crib layers is best seen in figure 9, which shows the load-displacement behavior of the support as a function of four parallelogram configurations (angles) for each of the four crib heights examined. Test results indicated that increasing the contact area provided a slight increase in load-carrying capability for the first 10 to 12 in of vertical displacement, after which the supports became more unstable, with continued displacement resulting in significantly less load-carrying capability as the contact area was increased.

The 45° configuration was significantly more unstable than the 60° configuration at the larger displacements and lost load-carrying capability fairly quickly after reaching maximum capacity. The change in contact area did not change the stiffness of the crib during elastic deformation (first 1 to 2 in of displacement), meaning the support resistance during the first 1 to 2 in of displacement was independent of crib

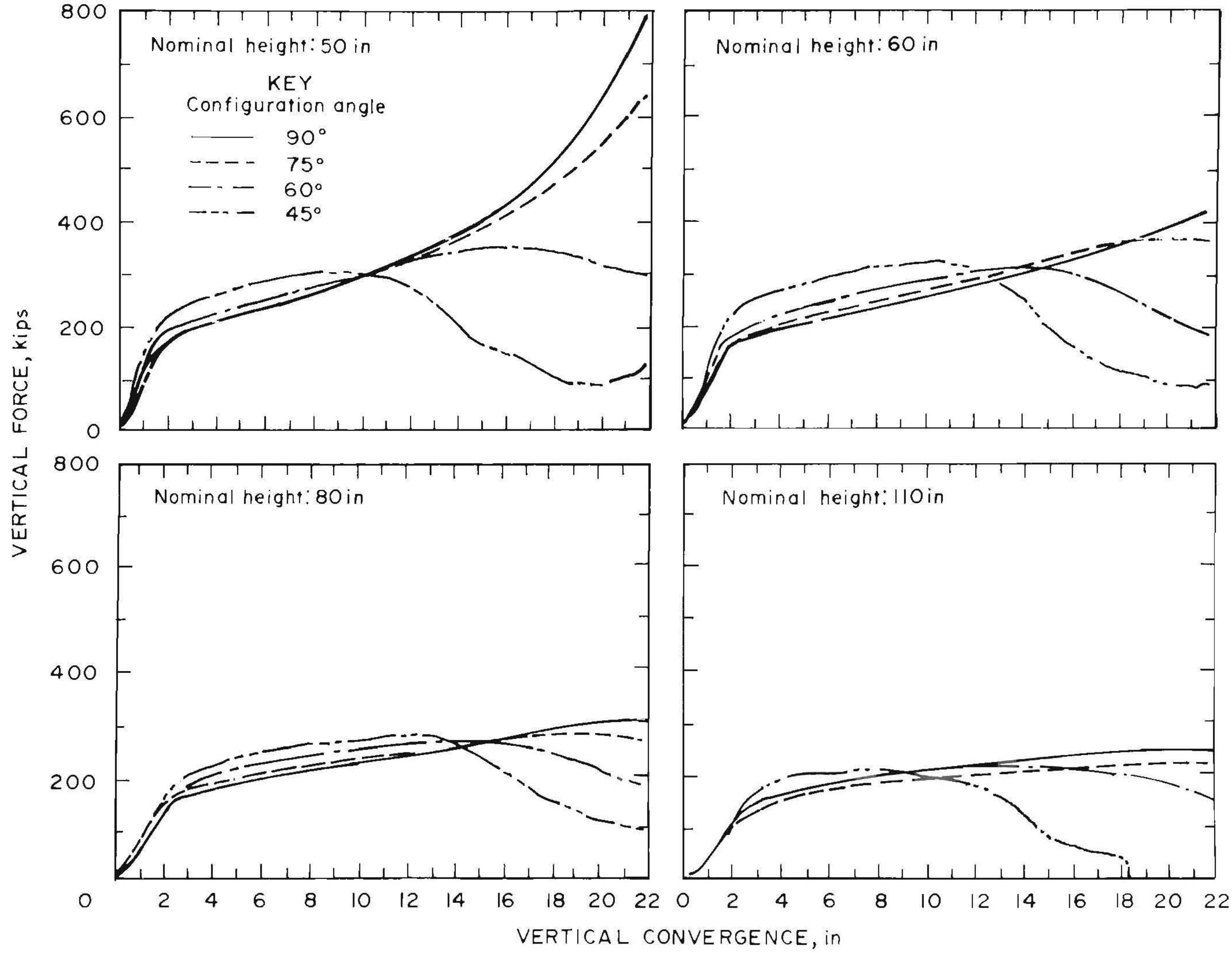


FIGURE 9.--Effect of increase in contact area on load-carrying capability of wood crib supports.

configuration. Some increase in load-carrying capability occurred during plastic deformation (2 to 10 in of displacement). As an example, a 38-pct increase in support resistance from 210 to 290 kips was observed for the 45° crib in comparison with the conventional 90° configuration at 6 in of vertical displacement, while the same 45° crib had 48 pct less support resistance at 16 in of vertical displacement. In comparison, the 60° configuration provided a 15-pct increase in support resistance compared with the 90° configuration at 6 in of displacement and a 7-pct reduction at 16 in of displacement.

In summary, the effect of increased contact area resulting from decreasing the angle of intersection between crib layers was that the wood crib capacity first increased slightly and then decreased, relative to the vertical displacement of the crib structure. The displacement at which behavior changed from increased resistance to decreased resistance appears to be a function of the height of the crib. The displacement at which the larger contact area no longer contributed to greater support resistance was found to increase as the height of the crib increased from 50 to 80 in, but this trend was not consistent for the 45° configuration at the 110-in height.

HORIZONTAL DISPLACEMENT CONSIDERATIONS

The effect of horizontal displacement on the load-carrying capability of wood crib supports is best seen in figure 10, which shows the load-displacement behavior of the support as a function of three convergence ratios for each of the four crib heights evaluated. For the 110- and 80-in supports, horizontal displacements had virtually no effect on the load-carrying capability of the supports throughout the 22 in of vertical displacement. Some effect was observed for the 60-in crib, showing a reduction in support resistance for increases in horizontal displacement, becoming significant after approximately 16 in of vertical dislacement. The 50-in crib exhibited

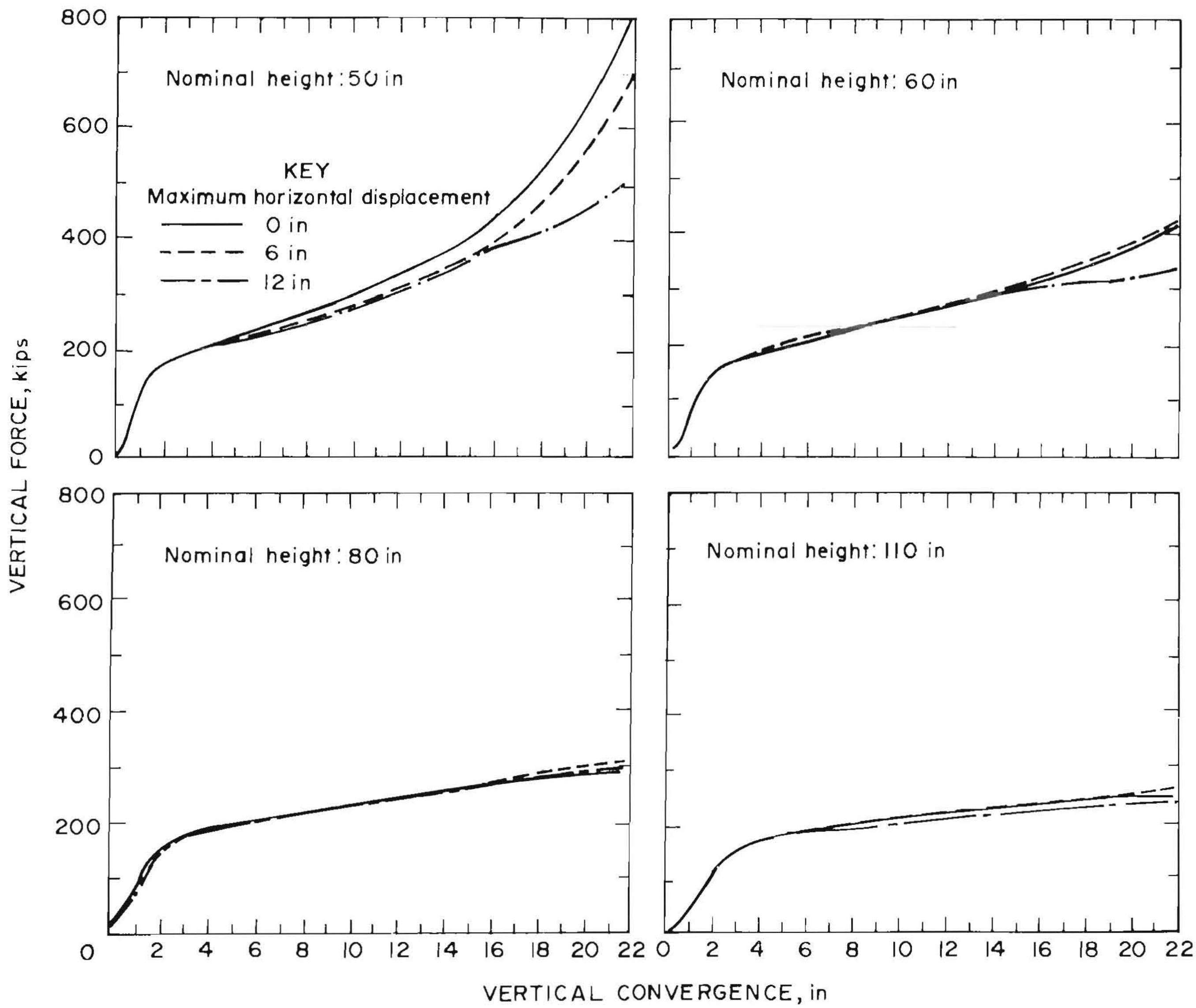


FIGURE 10.--Effect of horizontal displacements on load-carrying capability of wood crib supports.

the most change in behavior due to the presence of horizontal displacement, showing an approximate 35-pct reduction in support resistance for the maximum horizontal displacement compared with no horizontal displacement at 22 in of vertical displacement.

Since the more acute configurations represent less stable structures, tests were made to see if horizontal displacements would contribute to their instability. The results were consistent with the conventional square-geometry evaluations; horizontal displacement did not significantly contribute to the instability of the more acute configurations. Some reduction in support resistance was observed for increases in horizontal displacement at very large vertical displacements (greater than 15 in) for the 75° and 60° configurations, but these displacements are considered beyond the range of vertical convergence likely to be experienced underground.

It was also noticed that there was no change in behavior when the horizontal displacement was provided in the direction of the minor axis as compared with displacement in the direction of the major axis of the parallelogram. This behavior is seen in figure 11 where the 105° angle represents displacement in the major axis of the 75° crib configuration. Likewise, the 120° configuration is the complement of the 60° configuration.

In summary, reductions in height increase the load-carrying capability of wood crib supports, with the impact becoming more substantial as the vertical displacement increases. Horizontal displacement further reduces the load-carrying capability of the support,

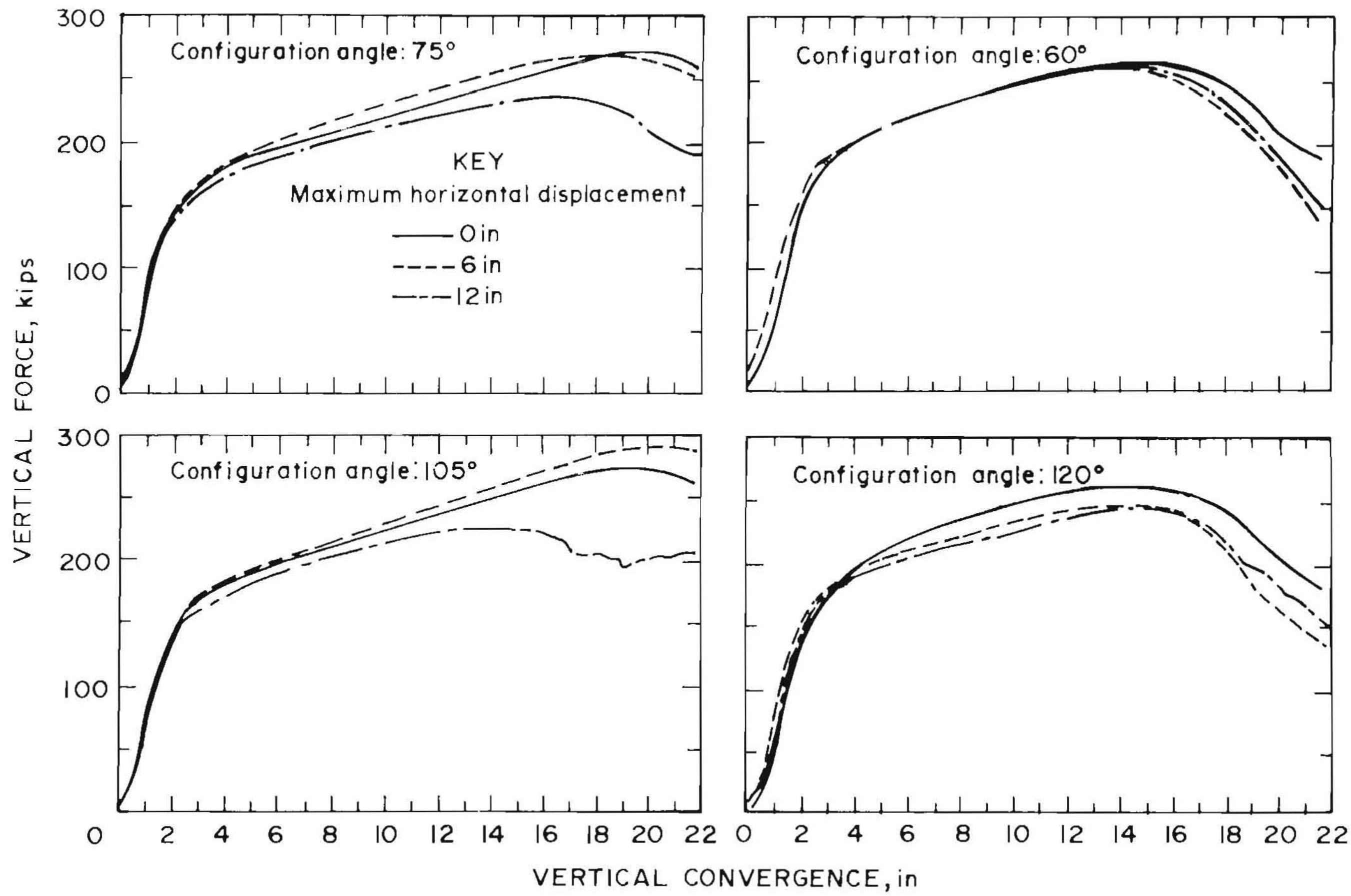


FIGURE 11.–Effect of horizontal displacements applied to major and minor axes of parallelogram crib configurations.

but only for large vertical convergence (beyond 10 in). Therefore, it is concluded that horizontal displacement will not have an effect on the load-carrying capability of wood cribs under most mine conditions where roof-to-floor convergence is likely to be less than 10 in.

OBSERVATION OF FAILURE MECHANICS

From observation of the tests, it appears that the primary failure mechanism for wood crib supports is instability (buckling), probably caused by differential compression of individual crib blocks relating to variation in material properties for the wood block specimens. The behavior of wood cribs for vertical and biaxial (vertical and horizontal) displacement is shown in figure 12 and illustrated by assimilation of the crib as a structural column in figure 13. Under vertical (axial) displacement, the wood crib is seen to displace in the middle of the structure (fig. 12*A*), which is consistent with the behavior of a structural column subjected to axial loads (fig. 13*A*). Horizontal displacements distort the profile to more of an S-shape as shown in figure 12*B*, again consistent with the behavior of a structural column (fig. 13*B*).

The basic requirement for any structural system is to maintain force and moment equilibrium. Horizontal displacements of the mine roof relative to the mine floor create a moment due to the axial vertical load's (resultant) no longer being applied in the same line of action. See figure 14*A* and equation 2:

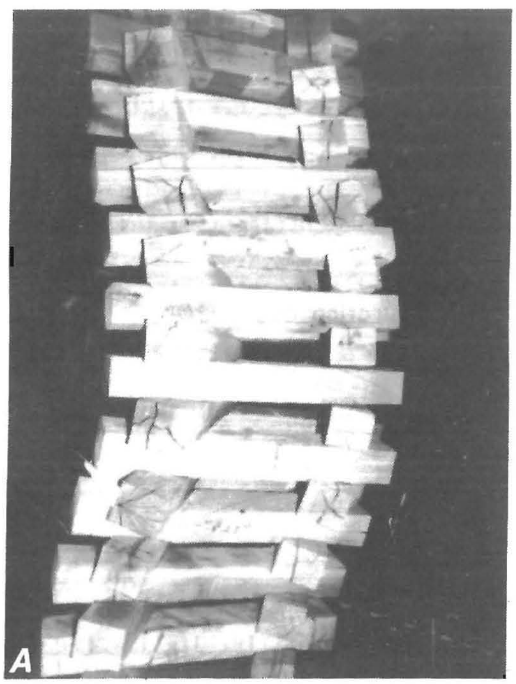
$$H\,(\ell) = V\,(\Delta h), \tag{2}$$

where H = horizontal force,

ℓ = height,

V = vertical force,

and Δh = horizontal displacement.



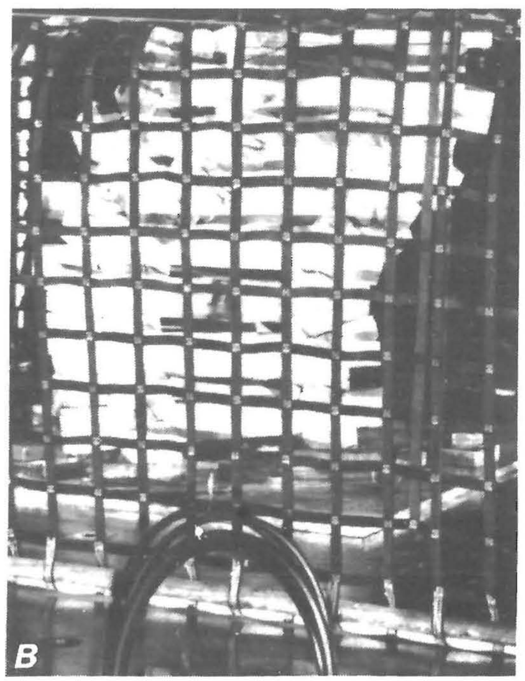


FIGURE 12.--Profile of crib structure during failure. *A*, **Without horizontal displacement;** *B*, **with horizontal displacement.**

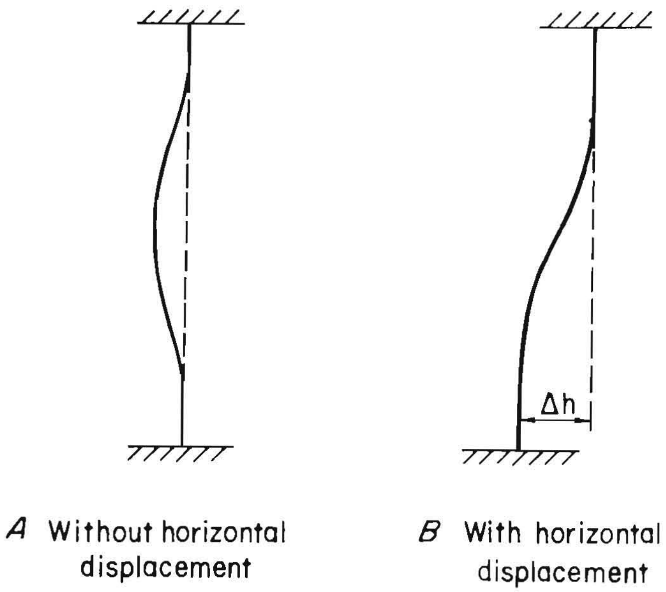


FIGURE 13.--Behavior of a structural column.

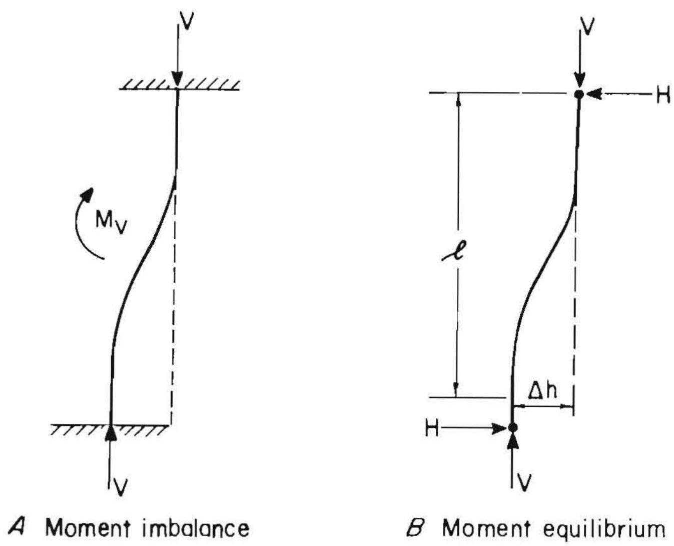


FIGURE 14.--Moment imbalance created in crib loading.

This vertical moment imbalance must be equilibrated by a horizontal force couple as shown in figure 14*B*. These moments induce buckling of the structure. Instability of the crib occurs when the support is incapable of transmitting these forces, both vertival and horizontal, through the structure to create the necessary force couples to maintain moment equilibrium.

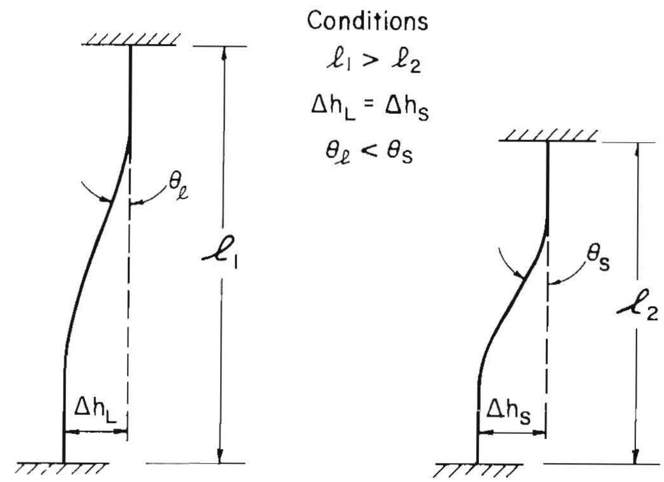


FIGURE 15.--Change in curvature as a function of crib height.

Test results revealed that horizontal displacements do not appreciably affect the stability of the wood crib, indicating that for the range of horizontal displacements evaluated (up to 12 in of horizontal displacement at 24 in of vertical displacement), the support was able to maintain force and moment equilibrium.

The test results also indicated that at large vertical displacement there was some reduction in support capacity due to horizontal displacement, and that this effect was more pronounced at shorter crib heights. This behavior can also be explained by assessment of moment equilibrium. From equation 2 and illustrated in figure 15, it is seen that as the height of the crib is reduced, larger horizontal forces must be generated for the same horizontal displacement to maintain moment equilibrium. It seems reasonable then that shorter cribs will have less capacity when subjected to horizontal displacements once the critical buckling strength is reached. This behavior can also be addressed by physical observation of the curvature (profile) of the structure. At higher heights, the curvature, which is a measure of moment, is less than it would be for shorter heights for the same horizontal displacement.

In general, it was seen that shorter cribs had larger capacity (vertical support resistance) than taller cribs. This behavior is also consistent with structural column mechanics. The buckling strength of a column is described by Euler's critical buckling equation, which relates the critical buckling load (P_{cr}) to the material modulus of elasticity (E), moment of inertia (I), and height of the column (L) by equation 3.

$$P_{cr} = \frac{(\pi^2 EI)}{L^2}. \qquad (3)$$

This relationship shows that the buckling strength increases for decreasing column heights. It is recognized that this equation is for elastic behavior only, and since wood crib failure typically occurs during plastic deformation, this equation is not directly applicable, but it is thought that a similar relationship exists for wood crib supports during plastic deformation.

Wood cribs are assumed to fail when either the compressive strength or buckling strength is exceeded. Increasing the contact area by changing the intersecting angle causes an increase in compressive strength but decreases the buckling strength of the support in the direction of the minor axis (see figure 4). As shown in table 1, test results are consistent with these conclusions. The table compares expected crib capacity, which would result for increases in contact area assuming no reductions in buckling strength, with actual support capacity from the tests. As seen from the table, less support capacity was observed than suggested from the contact area increases, substantiating the conclusion that some of the benefits derived from increases in compressive strength are offset by reductions in buckling strength.

TABLE 1. - Comparison of crib capacity for increases in contact areas (60-in crib height)

Configuration.......deg..	90	75	60	45
Contact area........in^2..	144	149	166	204
Expected load, kips, at--				
5-in displacement......	205	212	237	291
10-in displacement.....	250	259	288	354
15-in displacement.....	307	317	354	435
Observed load, kips, at--				
5-in displacement......	205	210	230	277
10-in displacement.....	250	258	272	320
15-in displacement.....	307	317	302	300

It is also seen from Euler's buckling equation that reductions in moment of inertia reduce the buckling strength of a column. Reductions in the moment of inertia for changes in crib geometry (angle of layer intersection) are shown in figure 16. From the figure it is seen that the minimum moment of inertia (see figure 4) is reduced as the configuration becomes more acute (reduction in intersecting angle). Considerations in the calculation of the moment of inertia for wood crib supports are documented in appendix C.

Another observation is that instability (buckling) did not occur along the minor or major axis of the intersecting contact points of the parallelogram. The support usually buckled along an axis oriented between the contact intersection points as shown in figure 17. This behavior is consistent with moment-of-inertia calculations (see appendix C), which determined the principal minimum moment-of-inertia axis to be oriented in this fashion (between the contact intersection points).

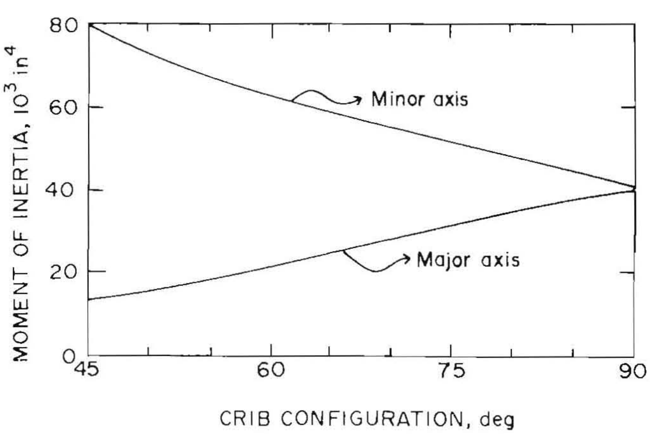


FIGURE 16.–Reduction in moment of inertia for various wood crib configurations.

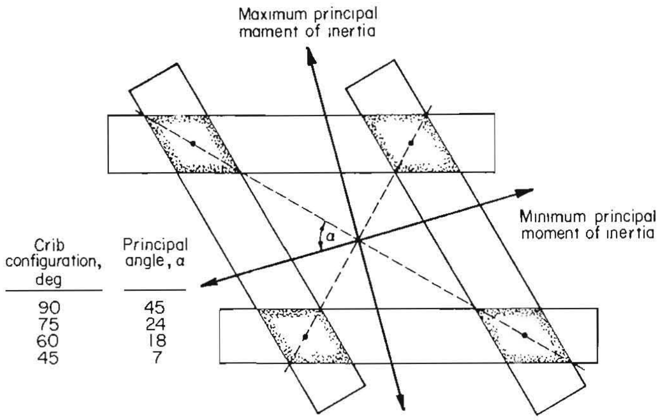


FIGURE 17.--Principal moment-of-inertia axis.

It was also observed that horizontal displacements did not appreciably affect the load-carrying capability of the acute configurations investigated in this study. This is consistent with biaxial displacement studies conducted on conventional 90° geometries, where it was concluded that the support is capable of deforming sufficiently to transmit horizontal forces produced by force couple systems necessary to maintain force and moment equilibrium.

Since the moment of inertia of the major axis of the parallelogram is substantially less than that of the minor axis, one might expect that the crib response to horizontal displacements in the major axis would be different from response to displacements in the direction of the minor axis. However, the test results revealed nearly the same crib response for horizontal displacement in either axis. This is explained by the determination that the principal moment-of-inertia axes are not oriented in the same reference as the axes defined by the points of intersection of the crib blocks. In other words, the crib does not fail in relation to the points of intersection axes; hence, the behavior is seen to be independent of displacements in this reference frame.

CONCLUSIONS

This Bureau study is part of a research program intended to optimize the load-carrying capability and compatibility of mine roof support systems with the strata conditions in which they must function. Three parameters affecting the strength and stability of wood crib supports were evaluated in this study: (1) height, (2) configuration, and (3) horizontal displacement.

Since strata behavior is not restricted to vertical (roof-to-floor) convergence, the effect of horizontal displacements is an important consideration in the evaluation of mine roof support systems, particularly passive supports such as wood cribbing. This study is a first attempt to quantitatively determine the effect of biaxial displacements on the load-carrying capability of wood cribs. It is also a first attempt to evaluate configurations other than conventional square geometries.

Conclusions drawn from this research are summarized as follows.

1. Horizontal displacements do not appreciably affect the load-carrying capability of wood crib supports for the range of vertical convergence (less than 10 in) likely to be encountered underground.
2. There is some reduction in support capacity (vertical support resistance) for large vertical convergence (greater than 10 in), with a trend of reduced capacity with increasing horizontal displacement.
3. In general, under the same load conditions, shorter wood crib structures have greater support resistance and are stiffer than taller cribs.
4. The behavior of wood cribs subjected to biaxial displacements is qualitatively consistent with the behavior of structural columns and obeys the laws of force and moment equilibrium.
5. Wood cribs fail when either the compressive strength or the buckling strength of the crib pillar is exceeded.

6. Changing the angle of intersection between crib layers increases the contact area and hence the compressive strength of the crib but decreases its buckling strength because of reductions in moment of inertia for the more acute configurations.

7. Increasing the contact area provides a slight increase in load-carrying capability for the first 10 to 12 in of vertical convergence, after which the cribs become more unstable with continued convergence, resulting in significantly less load-carrying capability as the contact area increases.

8. The effects observed above (item 7) become more pronounced as the crib height is reduced.

9. Horizontal displacements do not contribute significantly to the instability of the parallelogram geometries and therefore do not significantly affect the load-carrying capability of the support.

In summary, it is concluded that the benefits of a slight increase in load-carrying capability derived by the more acute configurations are outweighed by greater instability of the more acute configurations, promoting a recommendation to use conventional 90° geometries for wood crib construction. If additional strength is required, it is suggested that consideration be given to concrete crib supports or the utilization of three-block-per-layer wood crib supports. It is also concluded that wood cribs can be safely employed in conditions of large horizontal displacements.

APPENDIX A.--DESCRIPTION OF MINE ROOF SIMULATOR

The mine roof simulator (MRS) is a large hydraulic press (see figure 1 of text) designed to simulate the loading of full-scale underground mine roof supports. The MRS is unique in its abilities to apply both a vertical and a horizontal displacement simultaneously.

Both the vertical and horizontal axis can be programmed to operate in either force or displacement control. This capability permits tests such as true friction-free controlled loading of shields, which cannot be accomplished in uniaxial test machines since the shield develops a horizontal reaction to vertical roof convergence. Friction-free tests of this nature can be accomplished in the MRS by commanding a zero horizontal load condition, which allows the platen to float in the horizontal axis. Likewise, the MRS can apply controlled horizontal loading to a shield support, whereas uniaxial test machines can apply only vertical loading with no control over horizontal load reactions or capability to provide a specified horizontal load to the structure. The controlled displacement capability allows determination of a structure's stiffness, which is essential to understanding the load-displacement characteristics of the structure.

The machine incorporates 20-ft-square platens with a 16-ft vertical opening enabling full-scale testing of longwall roof support structures. Capacity of the simulator is 1,500 tons of vertical force and 800 tons of horizontal force and controlled displacement ranges of 0 to 24 in vertically and 0 to 16 in horizontally. Load and displacement control is provided in four ranges operating under a 12-bit analog-to-digital closed-loop control network, providing a load control capability of better than 0.1 kips (100 lb) and displacement control capability of better than 0.001 in. in the smallest load-displacement range.

Machine control and data acquisition are achieved with a computer. Eighty-eight channels of test article transducer conditioning are provided. Data acquisition is interfaced with the control network so machine behavior can be controlled by response of the test article instrumentation. For example, tests can be terminated or held when strain values reach a designated level in specified areas of a support structure. High-speed data acquisition is available with a separate computer at a rate of 300 samples per second. An X-Y-Y recorder provides real-time plotting of three data channels while all data are stored on computer disks for subsequent processing and analysis.

APPENDIX B.--INDIVIDUAL WOOD CRIB SPECIMEN TESTS

The repeatability among individual wood crib specimens is illustrated in figures B-1 through B-6, which depict load-displacement plots for tests on three crib supports for each load condition evaluated in this study.

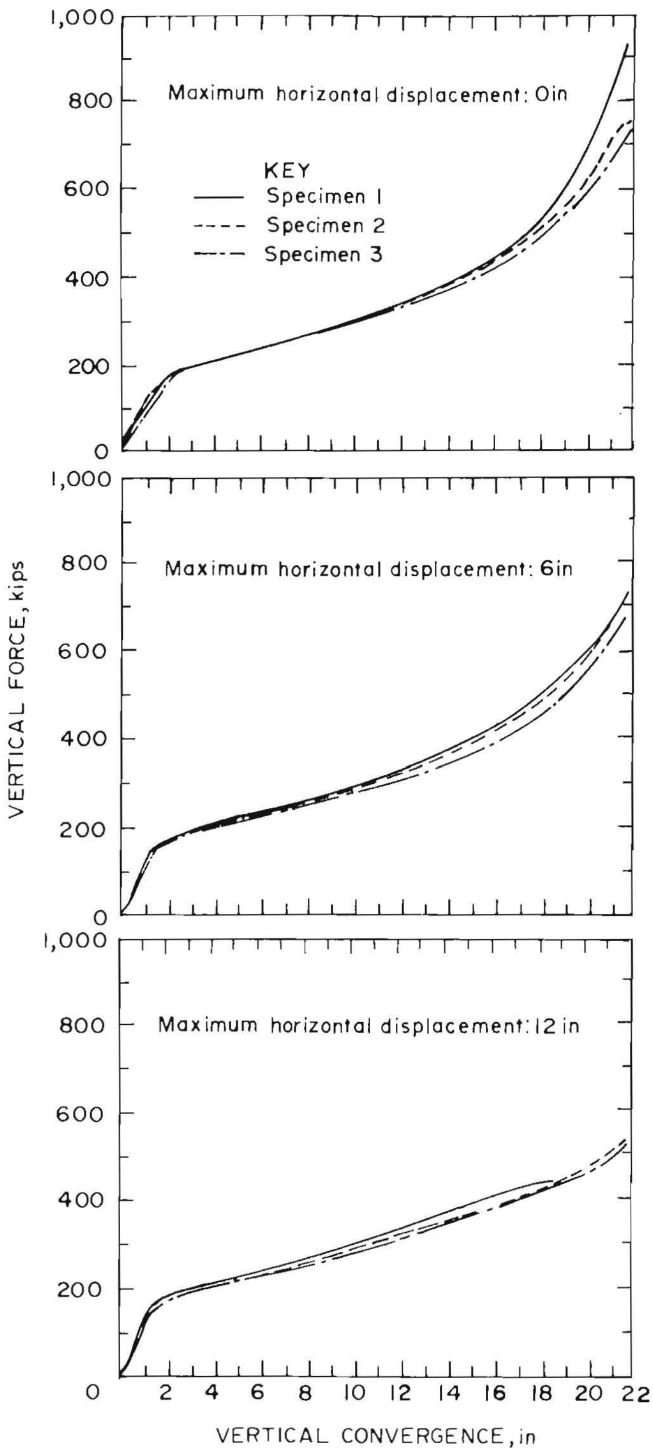


FIGURE B-1.--Repeatability of wood crib specimens (90° crib configuration, 50-in height).

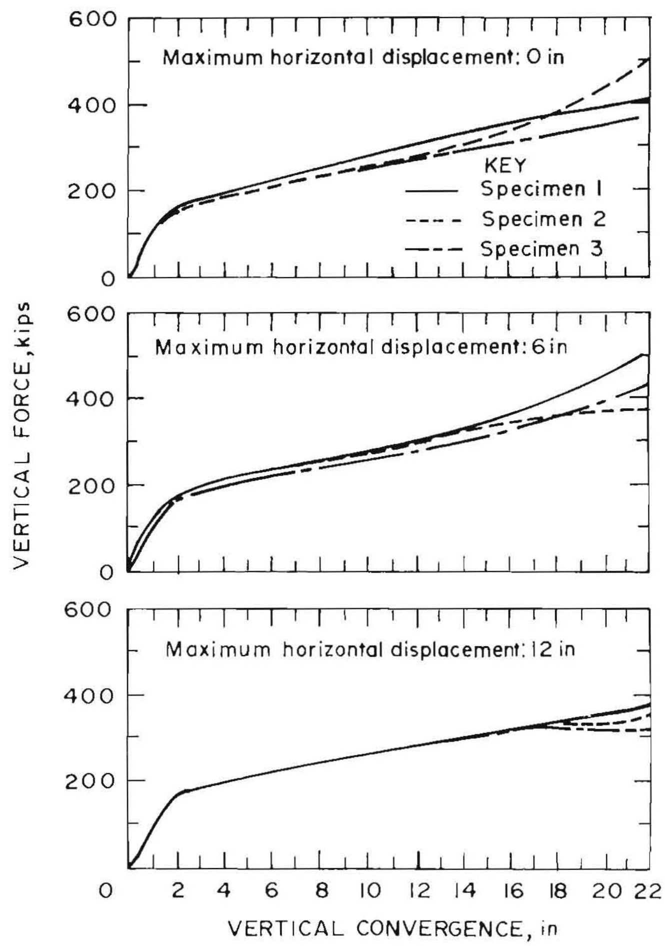


FIGURE B-2.--Repeatability of wood crib specimens (90° crib configuration, 60-in height).

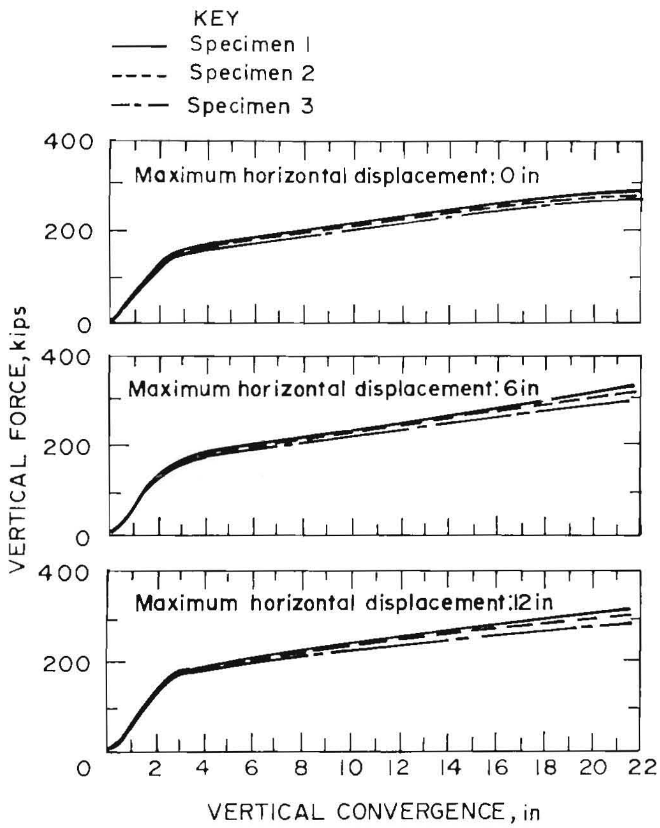


FIGURE B-3.--Repeatability of wood crib specimens (90° crib configuration, 80-in height).

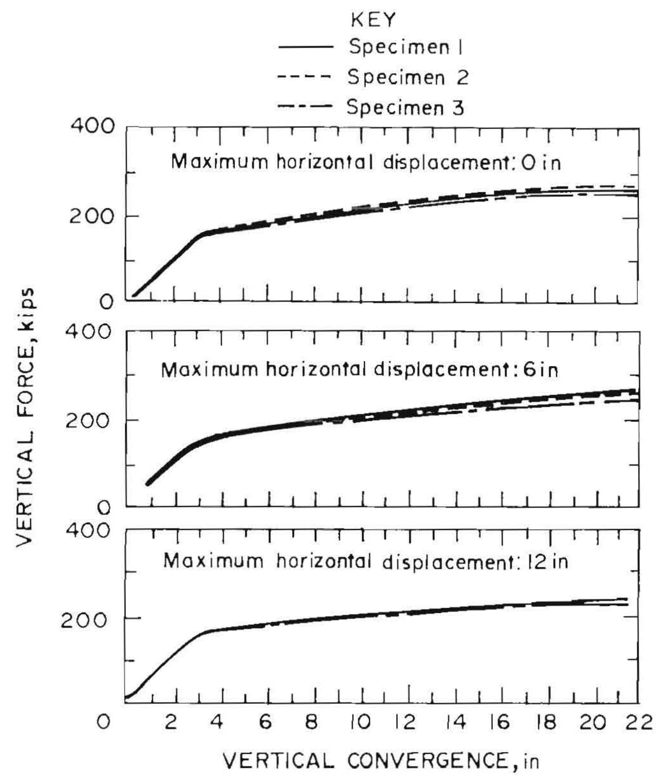


FIGURE B-4.--Repeatability of wood crib specimens (90° crib configuration, 110-in height).

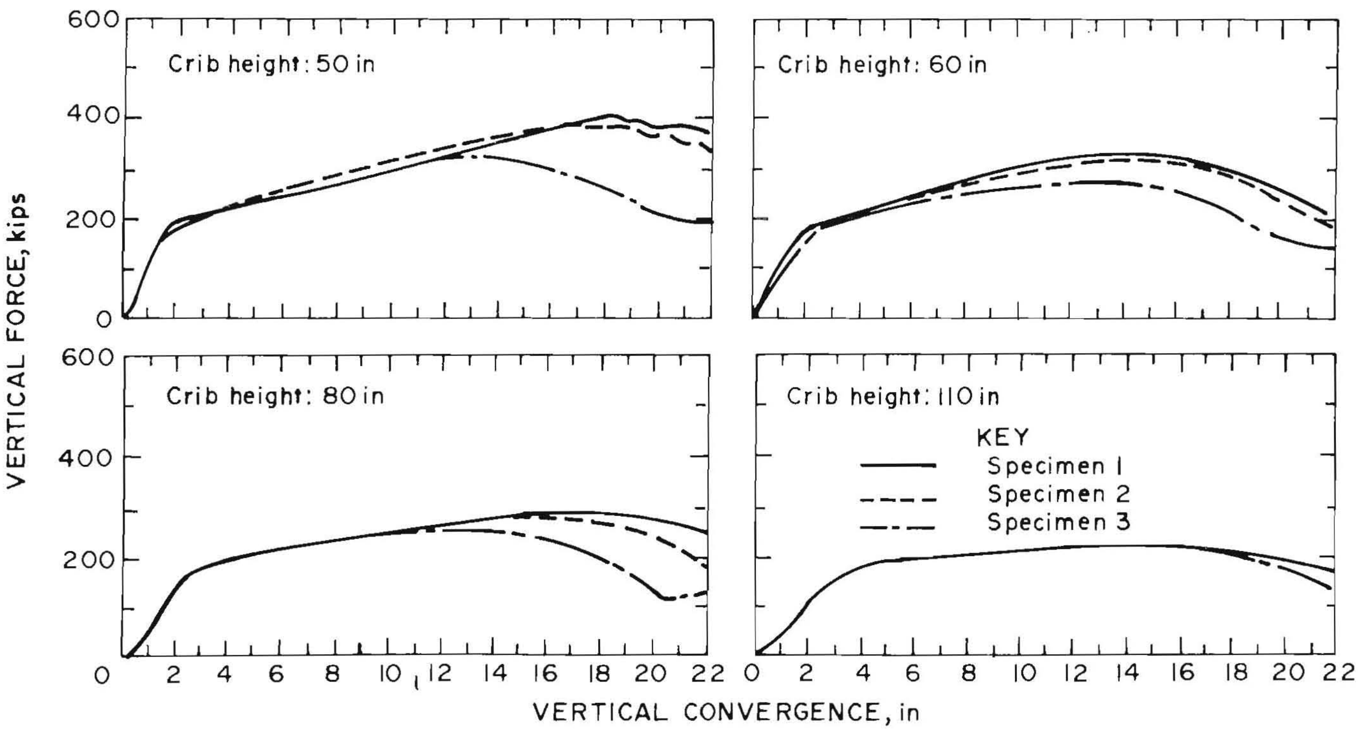


FIGURE B-5.--Repeatability of wood crib specimens (60° crib configuration).

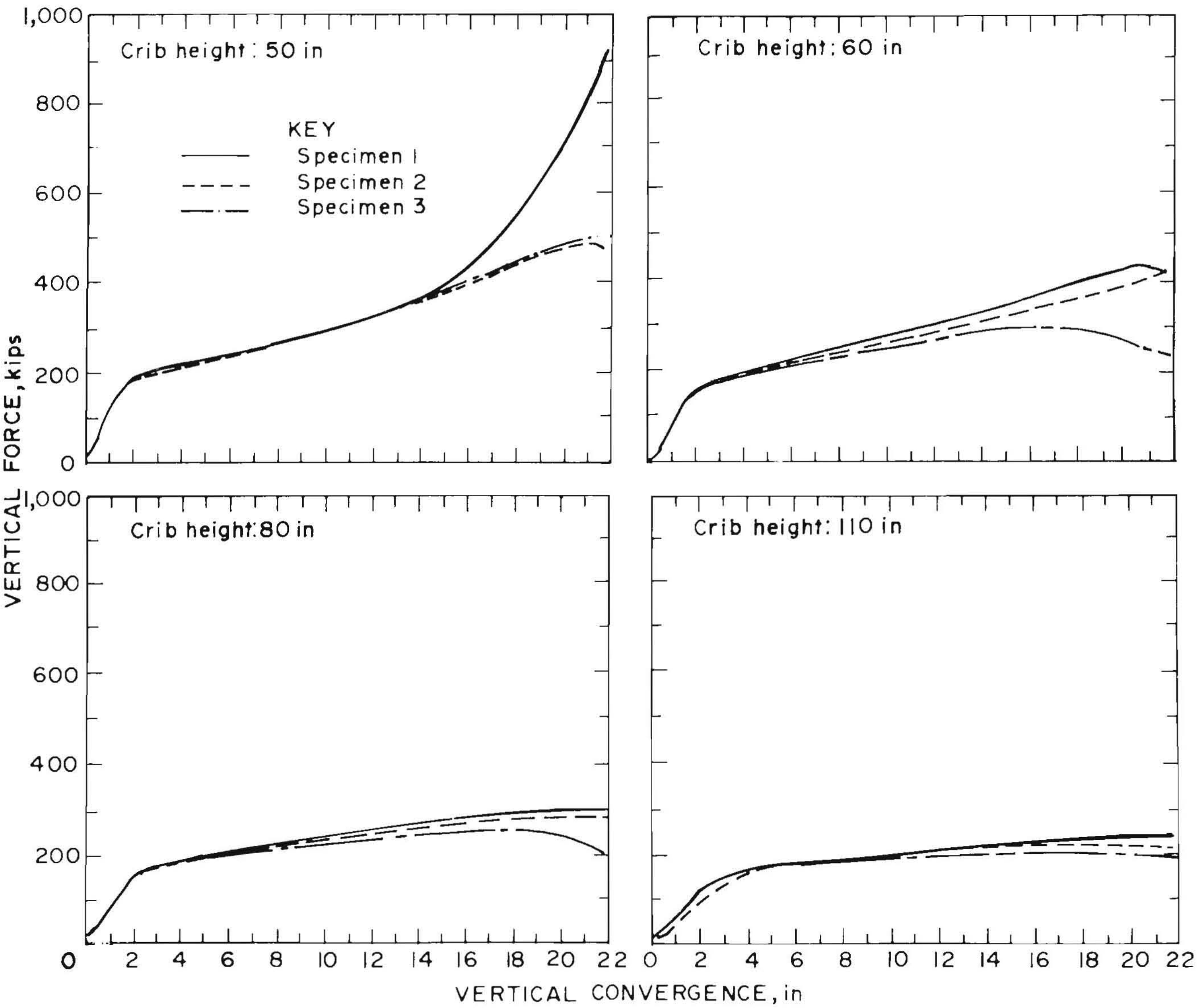
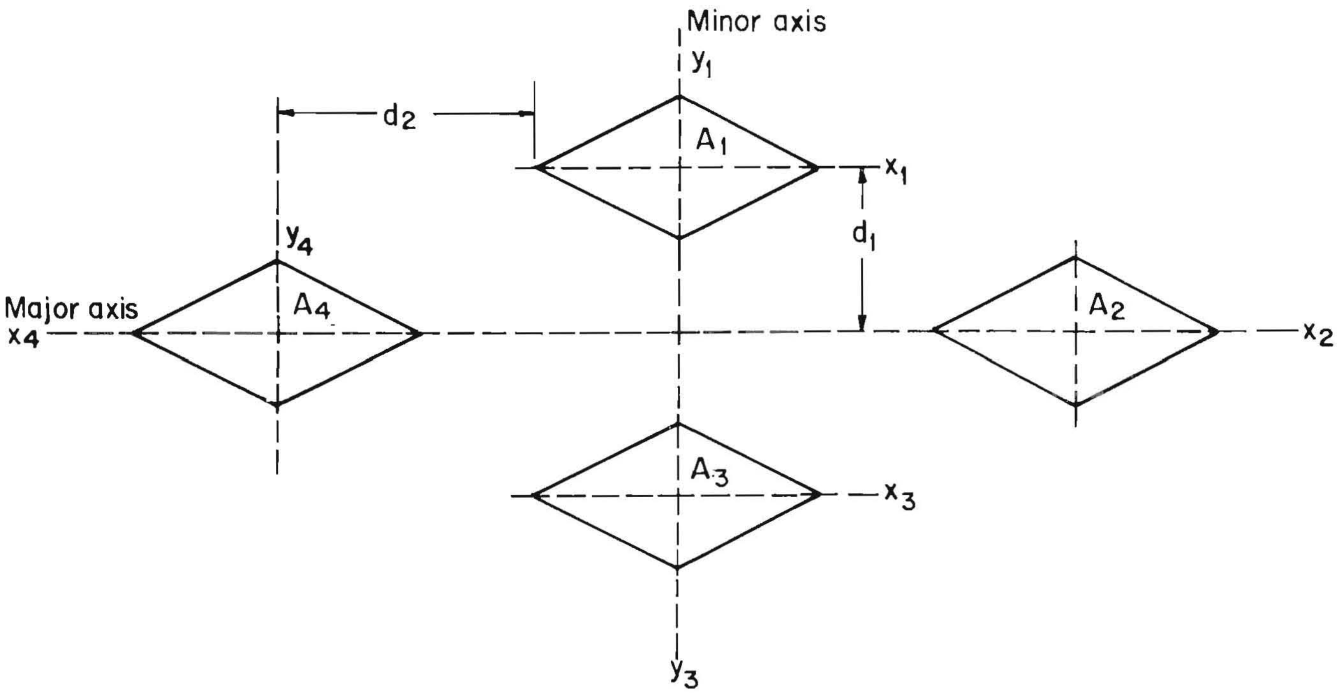


FIGURE B-6.--Repeatability of wood crib specimens (75° crib configuration).

APPENDIX C.--MOMENT-OF-INERTIA CONSIDERATIONS

One of the objectives of this study was to evaluate the stability of various wood crib geometries. Moment of inertia, an important consideration in evaluating stability of structures, was pursued in describing observed wood crib behavior. Moment-of-inertia determinations of wood crib supports are somewhat difficult. Wood cribs form open structures, and it is unclear exactly how the geometry contributes to stability of the structure.

Two approaches were attempted. The first approach was to determine moments of inertia for the four contact areas as shown in figure C-1. This approach produced reasonable magnitudes, but the direction of the principal moment-of-inertia axes was inconsistent with observed crib failure. The cribs were observed to fail (buckle) somewhere between contact areas. If the moment of inertia is determined only from contact areas,



Moment-of-inertia determinations

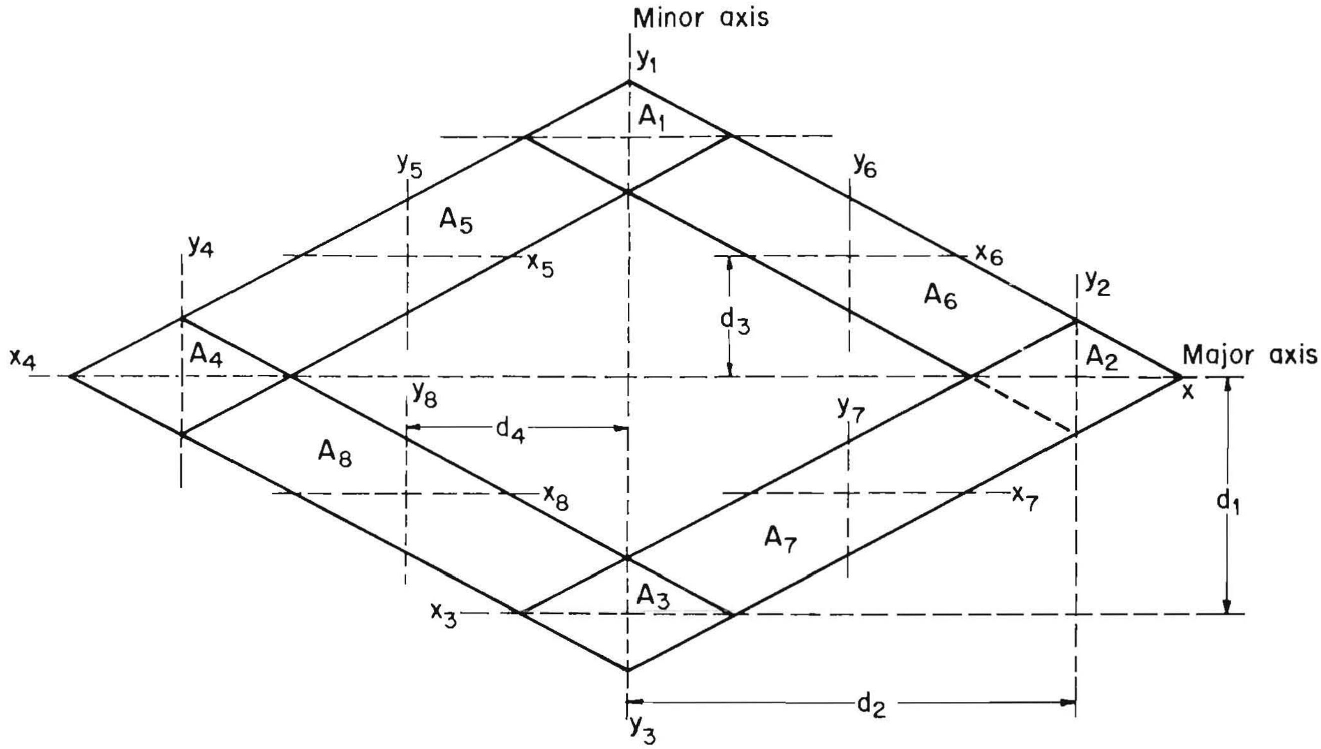
$$I\ \text{major} = I_{x_1}^{A_1} + I_{x_2}^{A_2} + I_{x_3}^{A_3} + I_{x_4}^{A_4} + A_1 d_1^2 + A_3 d_1^2$$

$$I\ \text{minor} = I_{y_1}^{A_1} + I_{y_2}^{A_2} + I_{y_3}^{A_3} + I_{y_4}^{A_4} + A_4 d_2^2 + A_2 d_2^2$$

FIGURE C-1.--Moment-of-inertia determination from contact areas.

the principal moment of inertia axes are oriented in the direction of the parallelogram axes.

It was concluded that moments of inertia of wood crib supports are more correctly determined by consideration of the full crib block as illustrated in figure C-2. Figure 11 in the text showed moments of inertia determined in this manner for the parallelogram axes. Principal moments of inertia are illustrated in figure C-3 and table C-1. From



Moment-of-inertia determinations

$$I\ \text{major} = I^{A_1}_{x_1} + I^{A_2}_{x_2} + I^{A_3}_{x_3} + I^{A_4}_{x_4} + A_3 d_1^2 + A_2 d_2^2 + I^{A_5}_{x_5} + I^{A_6}_{x_6} + I^{A_7}_{x_7} + I^{A_8}_{x_8} + A_5 d_3^2 + A_6 d_3^2 + A_7 d_3^2 + A_8 d_3^2$$

$$I\ \text{minor} = I^{A_1}_{y_1} + I^{A_2}_{y_2} + I^{A_3}_{y_3} + I^{A_4}_{y_4} + A_4 d_2^2 + A_2 d_2^2 + I^{A_5}_{y_5} + I^{A_6}_{y_6} + I^{A_7}_{y_7} + I^{A_8}_{y_8} + A_5 d_4^2 + A_6 d_4^2 + A_7 d_4^2 + A_8 d_4^2$$

FIGURE C-2.–Moment-of-inertia determination from full crib block.

table C-1, it is seen that the principal moments-of-inertia axes are rotated by as much as 45° from the reference frame of the parallelogram axes and more consistent with observed crib behavior.

TABLE C-1. - Principal moments of inertia

Crib configuration, deg	Moments of inertia, in^4		Principal angle, deg
	Minimum	Maximum	
90...........	27,000	52,920	45
75...........	24,196	56,750	25
60...........	18,448	66,065	14
45...........	12,487	80,268	7

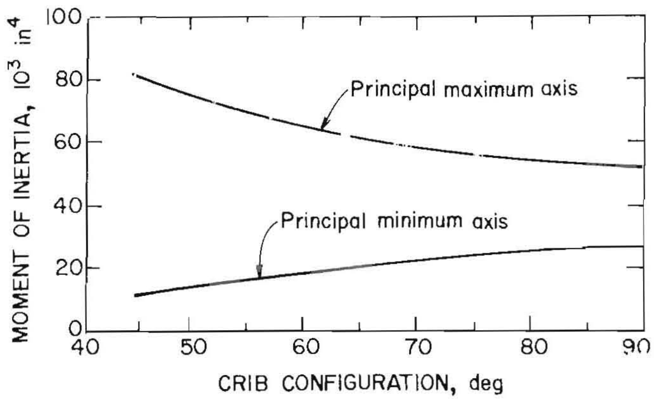


FIGURE C-3.--Principal moment-of-inertia reductions.

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