



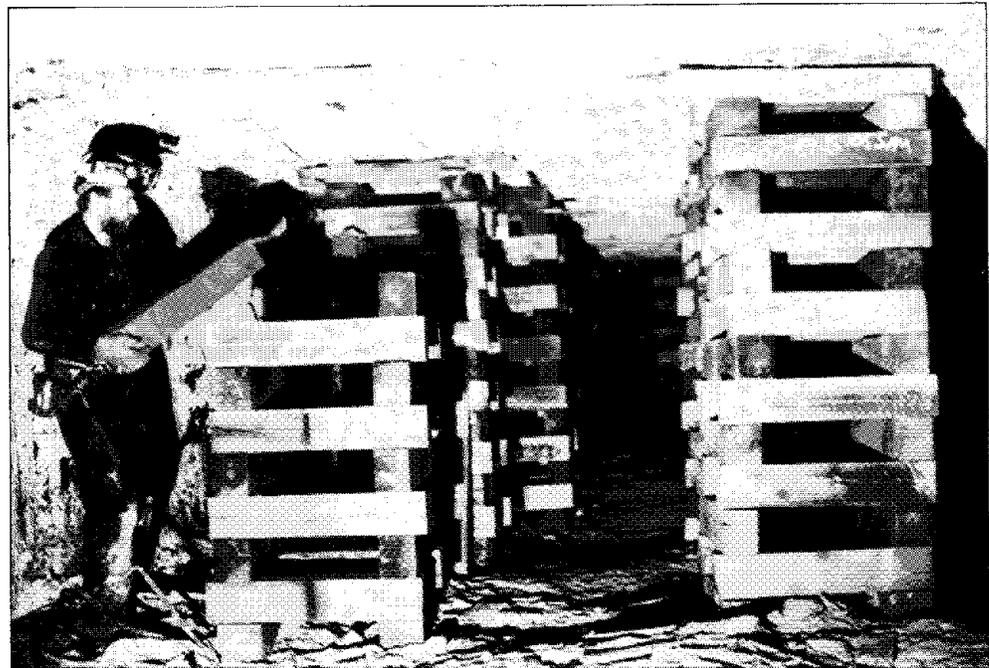
PB94-113552

INFORMATION CIRCULAR/1993

IC 9361

Engineering Methods for the Design and Employment of Wood Cribs

By Thomas M. Barczak and David F. Gearhart



United States Department of the Interior



Bureau of Mines

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Cover Photograph: Installation of cribs in longwall tail-gate entry. (Photo by Frank Chase, Pittsburgh Research Center, Pittsburgh, PA)

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Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (9704-0188).

| | | |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------|--------------------------------------------------|
|  PB94-113552 | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED IC -9361 |
| 4. TITLE AND SUBTITLE Engineering Methods for the Design and Employment of Wood Cribs | | 5. FUNDING NUMBERS |
| 6. AUTHOR(S) Thomas M. Barczak and David F. Gearhart | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Bureau of Mines Pittsburgh Research Center P.O. Box 18070 Pittsburgh, PA 15236 | | 10. SPONSORING/MONITORING AGENCY REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Bureau of Mines Research 810 7th Street, NW Washington, DC 20241 | | 11. SUPPLEMENTARY NOTES |
| 12A. DISTRIBUTION/AVAILABILITY STATEMENT | | 12B. DISTRIBUTION CODE |
| 13. ABSTRACT (Maximum 200 words) Wood cribs are used extensively by the mining industry to stabilize mine openings. While the cost per crib is relatively low, the extensive use can result in annual mine costs of over 1 million dollars. In an effort to improve the utilization of these supports and to reduce ground control hazards, the U.S. Bureau of Mines has developed engineering methods to assist mine operators in wood crib design and employment. Design and employment criteria are established based on the strength, stiffness, and stability of the crib structure in relation to the load conditions imposed by the mine environment. Models have been developed based on full-scale tests in the Bureau's Mine Roof Simulator that compute the capacity of wood cribs of various configurations and material constructions as a function of displacement of the crib structure due to roof-and-floor convergence. These models permit comparison of the loading characteristics and costs of employment of different crib designs, and in conjunction with roof behavior models, provide a means to determine the optimum design and employment strategy. | | |
| 14. SUBJECT TERMS | | 15. NUMBER OF PAGES 16. PRICE CODE |
| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT |
| 20. LIMITATION OF ABSTRACT | | |

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UNITED STATES DEPARTMENT OF THE INTERIOR
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Library of Congress Cataloging in Publication Data:



PB94-113552

Barczak, Thomas M.

Engineering methods for the design and employment of wood cribs / by Thomas M. Barczak and David F. Gearhart.

p. cm. — (Information circular; 9361)

Includes bibliographical references (p. 25).

1. Mine timbering—Design and construction. 2. Mine timbering—Testing. I. Gearhart, David F. II. Title. III. Series: Information circular (United States. Bureau of Mines); 9361.

TN295.U4 [TN289] 622 s—dc20 [622'.28] 93-11141 CIP

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|-----------------|-----------------|--------------------|-----------------------|
| \$/ft | dollar per foot | kip/in | kip per inch |
| ft | foot | lb | pound |
| h | hour | lb/ft | pound per foot |
| in | inch | lb/ft ³ | pound per cubic foot |
| in ² | square inch | lb/in ³ | pound per cubic inch |
| in/h | inch per hour | pct | percent |
| in/min | inch per minute | pct/min | percent per minute |
| kip | 1,000 pound | psi | pound per square inch |
| kip/ft | kip per foot | s | second |

ENGINEERING METHODS FOR THE DESIGN AND EMPLOYMENT OF WOOD CRIBS

By Thomas M. Barczak¹ and David F. Gearhart²

ABSTRACT

Wood cribs are used extensively by the mining industry to stabilize mine openings. While the cost per crib is relatively low, their extensive use can result in annual mine costs of over \$1 million. In an effort to improve the utilization of these supports and to reduce ground control hazards, the U.S. Bureau of Mines has developed engineering methods to assist mine operators in wood-crib design and employment. Design and employment criteria are established based on the strength, stiffness, and stability of the crib structure in relation to the load conditions imposed by the mine environment. Models have been developed based on full-scale tests in the USBM's Mine Roof Simulator that compute the capacity of wood cribs of various configurations and material constructions as a function of displacement of the crib structure due to roof-and-floor convergence. These models permit the comparison of the loading characteristics and costs of employment of different crib designs, and in conjunction with roof behavior models, provide a means to determine the optimum design and employment strategy.

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INTRODUCTION

As voids are created because of the extraction of coal underground, artificial support systems, in addition to roof bolting, often are required to stabilize the mine opening to provide a safe working environment. Various constructions of cribs made from wood timbers are used most often. Although these supports are simple in design with a unit material cost of less than \$20/ft of construction height, their extensive use in providing essential ground control adds a significant cost to coal mining. One operator estimates that \$1 million are spent annually in the construction of cribs to support the mine's longwall gate roads.³ It is estimated that nearly 500,000 short tons of wood material are used annually for roof support in underground coal mines in the United States. As the supply of wood diminishes, the cost of crib support will continue to increase.

The goal in the design and employment of these supplemental support systems is to stabilize the mine opening at a minimal cost without sacrificing safety. Mine operators need to know the performance characteristics of different support configurations to select the optimum design and employment strategy. Conservative employment strategies generally are used since the performance of the support system and in-mine load conditions are not well known. When load conditions exceed the capability of the support system, entry stability is jeopardized and the safety of miners is threatened.

A review of 69 longwall gate roads found that crib spacings varied from 1 to 25 ft, with an average spacing of 7.9 ft and a standard deviation of 3.2 ft. Approximately 50 pct of these gate roads employed two rows of cribs across the entry. There was no statistical difference in crib spacings for single- and double-row employment, nor was there a difference in spacing associated with the size of the timber used in the crib construction. Timber width in these applications ranged from 5 to 12 in. All cribs were constructed with two timbers per layer. The lack of correlation between crib design and spacing suggest that optimum employment was not being pursued.

As part of the U.S. Bureau of Mines' mission to reduce hazards to the miner through the development of improved ground control technologies, the USBM conducted full-scale tests of various wood-crib designs under controlled loading conditions in the USBM's 3-million-lb load frame. These tests provided a meaningful comparison of performance and led to the development of a model that predicts the load-displacement behavior of wood cribs in which the type of wood, timber dimensions, and construction configuration are varied.

The culmination of these research efforts are engineering methods for the optimum design and employment of crib support systems. Optimum crib design and employment will conserve the use of the crib materials and minimize the cost of mining while reducing mining hazards.

ACKNOWLEDGMENTS

The authors wish to extend their deepest appreciation to Carol Tasillo, civil engineer, U.S. Army Corps of Engineers, Pittsburgh, PA, who performed many preliminary tests and analyses of wood cribs that provided the foundation of this report. They would also like to thank David E. Schwemmer, structural engineer, Eichleay Engineers, Inc., Pittsburgh, PA, who also participated in previous wood-crib research. Special thanks are given to Brian K. Mueller, project engineer, SSI Services, Inc., Pittsburgh, PA, who assisted in conducting recent wood-crib tests and in the preparation of the wood-crib predictive model. Finally, they would like to express their appreciation to the people who reviewed this report and

provided valuable contributions to its quality, including: Terry Hoch, chief, roof control division, Mine Safety and Health Administration, Pittsburgh, PA; Stephen Tadolini, mining engineer, Denver Research Center, U.S. Bureau of Mines, Denver, CO; Andrew Schissler, manager, technical resources, Cyprus Coal, Englewood, CO; Richard Repsher, staff engineer, U.S. Bureau of Mines, Washington, DC; Maurice Deul, associate professor, University of Pittsburgh, Pittsburgh, PA; John Wilson, chairman, mining engineering department, University of Missouri-Rolla, Rolla, MO; and Claude Goode, manager, test facilities, Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA.

SUPPORT CONSTRUCTION AND LOADING BEHAVIOR

Multitimbered wood cribs are constructed from layers of timbers stacked on top of one another in a

perpendicularly alternating orientation to form arrangements as shown in figure 1. Geometrically, the crib structure is generally a square or a rectangle. The height

³Private communication with mine operator.

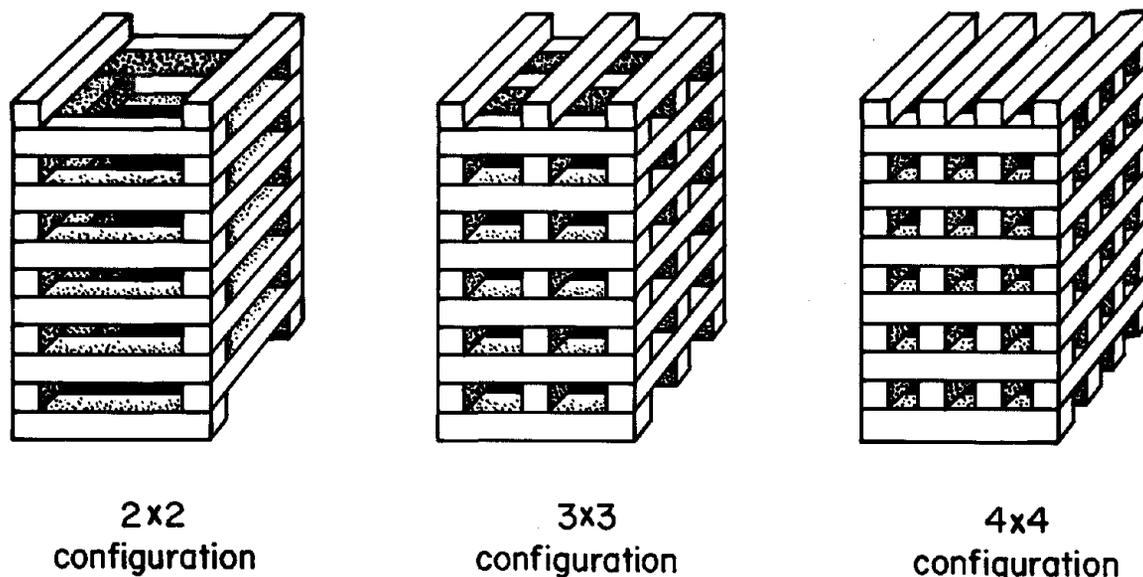


Figure 1.—Examples of multitimbered wood crib construction.

of the crib is determined by the number of timber layers, and the configuration is described by the number of timbers per layer. Two-timber-per-layer construction (2x2) is used most often in an effort to minimize unit costs. In eastern coal mines, wood cribs generally are constructed from hardwood timbers, while softwood timbers generally are used in western coal mines. Hardwood timber cross sections are typically 5 by 6 in or 6 by 6 in, while softwood timber cross sections are typically 8 by 8 in or 8 by 10 in. The minimum timber length is 30 in, as specified in the Code of Federal Regulations (1).⁴ Timber lengths typically range from 30 to 60 in.

The load-displacement relationship for a wood crib follows a distinct pattern as shown in figure 2 (2). Two regions of proportional behavior are followed by a nonlinear load-displacement relationship. Initially, the resistive force of a wood crib increases quickly as a linear function of displacement and is termed the linear elastic deformation phase. This behavior occurs during the initial 5-pct crib strain. The crib stiffness then decreases as the wood exhibits linear plastic deformation. Linear plastic deformation may occur at up to 25- or 30-pct crib strain. Finally, the crib stiffness increases nonlinearly and is identified as the nonlinear plastic deformation phase. Nonlinear plastic behavior typically begins at 20- to 30-pct strain for most

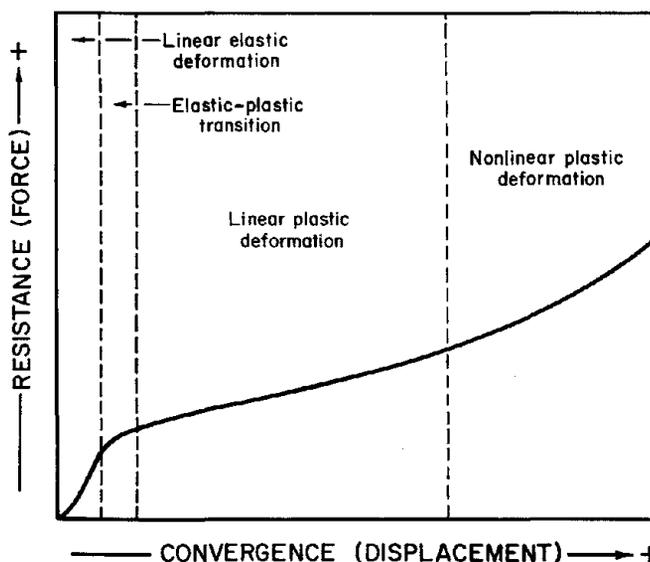


Figure 2.—Generalized load-deformation relationship for wood-crib support.

crib constructions. This region is where the cellular structure of the wood has collapsed and the ultimate strength of the crib is realized. Unstable structures seldom reach the nonlinear phase of plastic deformation.

DESIGN CRITERIA

The primary function of wood-crib support systems is to stabilize the immediate strata. This requires sufficient

crib capacity to support the weight of rock masses in the immediate roof that become detached from stable roof structures as a result of the stress distribution around the

⁴Italic numbers in parentheses refer to items in the list of references preceding the appendixes at the end of this report.

opening. Ideally, the cribs should help to prevent roof-and-floor failure by providing resistance to immediate strata deflections or movements along fracture planes. Since most mine openings continue to close through irresistible strata movements in response to nearby active mining, the cribs must be able to accommodate this convergence by yielding without a loss of stability.

Strength, stiffness, and stability are the design requirements that must be considered for an acceptable wood-crib support. Failure to evaluate these design considerations can lead to poor design and unacceptable performance.

Strength.—Strength is a measure of load capacity and typically refers to the maximum support capacity or its ultimate strength.

Stiffness.—Stiffness is a measure of how much resistive force will be developed by the support in response to displacement of the support structure. A stiffer support will react a larger force than a less stiff support for the same displacement.

Stability.—Stability is a measure of the capability of a support structure to maintain equilibrium through the action of internal forces or moments. A loss of load carrying capability generally is associated with instability.

Since wood cribs are passive supports and develop resistance through convergence of the mine roof and floor, the stiffness of the crib is the most critical design factor. Wood cribs should have adequate stiffness to provide resistance to roof loads within a displacement that will maintain roof stability. The design parameters that affect crib stiffness are the strength of the wood, the interlayer contact area, the number of timbers per layer, and the height of the structure. Crib stiffness will be maximized by increasing timber width, increasing the number of timbers per layer, and using a high-strength wood. A model that estimates wood crib stiffness based on the stiffness characteristics of individual timbers is shown in figure 3.

Stability is most dependent on the buckling of the crib structure. Wood cribs should remain stable without loss of load capacity through a displacement compatible with the convergence of the mine opening. Design factors that influence stability are the aspect ratio (height-to-width ratio) and the moment of inertia of the crib structure. Buckling effects become more prevalent as the moment of inertia decreases and as the aspect ratio increased. Buckling becomes more dominant at larger strains. (Strain is a measure of crib deformation defined as the ratio of the crib displacement to its original height.) Also, buckling is affected significantly by failure of a timber within the crib that causes differential displacements within a timber layer. Selection of the proper aspect ratio will ensure the stability of most cribs through 20-pct strain.

The strength of a crib is determined primarily by the compressive strength of the wood and the interlayer contact area. Wood cribs should have sufficient capacity to support the weight of rock masses that become detached from stable roof structures. Data on the compressive strength and mechanical properties of many species of wood are reported by the Forest Service of the U.S. Department of Agriculture and the American Society for Testing and Materials (3).

PARAMETERS THAT AFFECT THE STRENGTH OF WOOD

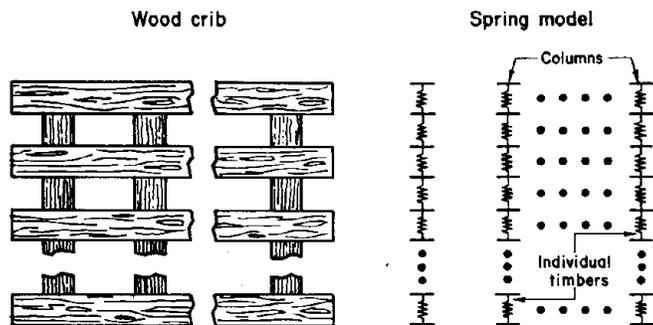
Mine timbers are loaded perpendicular to the grain in conventional wood crib applications. A standardized test by the American Society for Testing and Materials (ASTM) is used to determine the strength of wood perpendicular to the grain. The test is performed on a 6-in-long specimen with a 2- by 2-in cross section with the growth rings oriented in the direction of the applied load as shown in figure 4 (4). A 2-in-wide steel plate is placed on the center section of the specimen and a constant rate of displacement of 0.012 in/min is applied until the wood is compressed 0.1 in. The value of the stress at the proportional limit (completion of the linear elastic deformation illustrated in figure 3) is used to specify the strength of the wood. More recently, the value of stress at 0.04 in of displacement has been used to specify the compressive strength of the wood, since the proportional limit is not well defined (5).

The ASTM test to measure the hardness of wood uses a 0.444-in-diam steel ball that is pressed into a 2- by 2- by 6-in section of wood as shown in figure 5 (4). The force required to imbed the ball to half of its diameter determines the hardness. At this depth, the wood is stressed sufficiently to exhibit plastic deformation. The reported value is the average of the results from the loading applied in the radial and tangential directions of the wood fiber (see figure 6).

Several parameters are known to effect the strength of wood. These are described as follows.

Environmental Conditions

Wood is an organic material that is subject to widely varying environmental conditions that affect its physical and mechanical properties during its growth. Environmental factors that affect the strength of wood include the availability of water and damage sustained from wind and snow loads. Other factors include the presence of knots, insect damage, rate of growth, and decay.



Stiffness of one column:

$$1/K_C = 1/K_{T(1)} + 1/K_{T(2)} + \dots + 1/K_{T(L)}$$

$$K_{T(1)} = K_{T(2)} = \dots = K_{T(L)} = K_T$$

$$1/K_C = L * (1/K_T)$$

$$K_C = K_T / L$$

Stiffness of crib:

$$STIF = K_{C(1)} + K_{C(2)} + \dots + K_{C(N^2)}$$

$$K_{C(1)} = K_{C(2)} = \dots = K_{C(N^2)} = K_C$$

$$STIF = N^2 * K_C = (N^2 * K_T) / L$$

KEY

- K_T Stiffness of one timber
- K_C Stiffness of one column
- N Number of timbers per layer
- L Number of layers per crib
- STIF Stiffness of crib

Figure 3.—Wood-crib stiffness model.

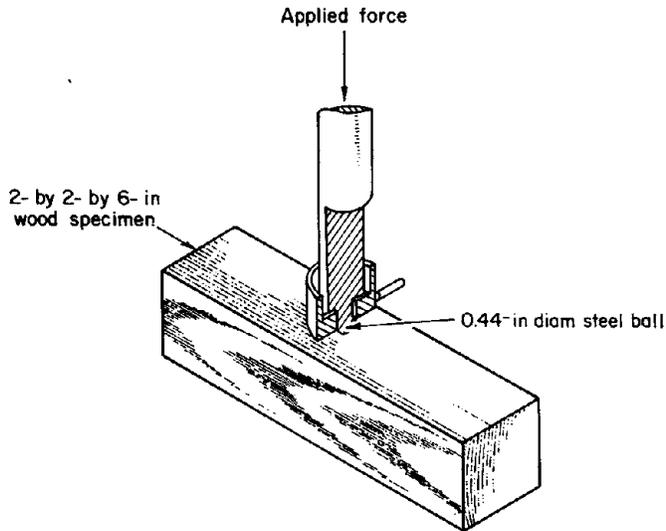


Figure 5.—ASTM test to determine the hardness of wood.

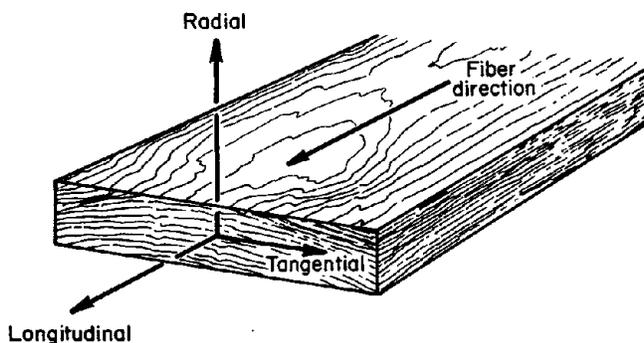


Figure 6.—Orthotropic nature of wood.

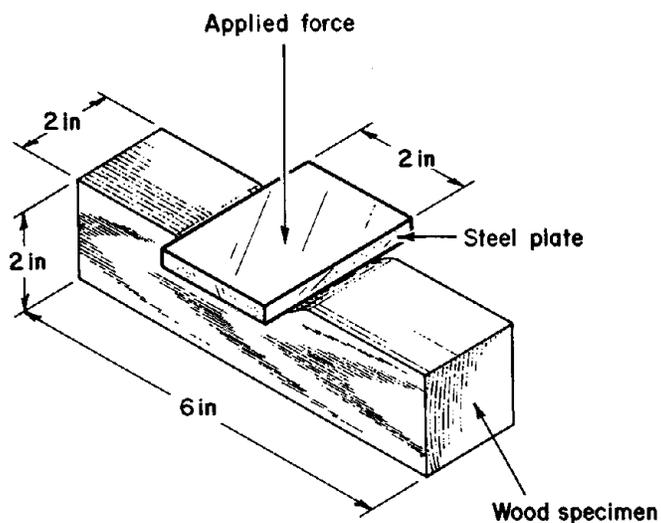


Figure 4.—ASTM test to determine the strength of wood perpendicular to the grain.

The treatment of wood during processing and service application also affects its mechanical properties. Drying the wood produces the most significant affect by creating defects that weaken the wood. Mine service conditions that affect the mechanical properties of wood include wet environments, rate of loading and duration of stress, fatigue, and age.

Species

The material properties of wood are highly dependent on the species of the tree. Species of trees are broadly classified as hardwoods or as softwoods. More accurately, the hardwoods are the broadleaf trees and the softwoods are the conifers. This broad classification does not reflect the actual hardness of the wood. Some species of softwoods have a higher compressive strength or hardness than some species classified as hardwoods. Examples of

used for mine timbers are oak, maple, birch, poplar, and elm. Softwoods used for mine cribbing include lodgepole pine, spruce pine, and fir. Hardwoods are abundant and available in the eastern coal regions, while softwoods are used primarily in the western coal regions.

Grain Orientation

Wood is an orthotropic material, meaning that it exhibits its unique and independent properties in the directions of three mutually perpendicular axes shown in figure 6 (3). Hence, the direction of the applied load, with respect to the grain of the wood, affects the results of the tests to determine material properties. For small specimens in which the grain orientation is controlled easily, the radial direction of load application yields a higher measurement of strength and hardness than tangentially applied loads as shown in figure 7.

Moisture Content

The amount of moisture present in the specimen also affects the material properties of the wood. Dry wood is considered to have 12 pct or less moisture content, while green wood has a moisture content of 25 to 35 pct (3). Small specimens of wood exhibit higher strength in the dry or seasoned condition than in the green condition. The ASTM-reported value of the compressive strength perpendicular to the grain is determined at 12-pct moisture content (4). A decrease of 6-pct moisture content (below this 12-pct level) increases the strength by 30 pct. An increase of 8-pct moisture content reduces the strength by 30 pct (3). Specimens with very high moisture content (>50 pct) have slightly higher strength than specimens in the green condition due to hydrostatic pressure in the cell structure (6). Moisture content has less effect on timbers larger than 4 in thick because the increase in strength due to reduced moisture is offset by defects created during the drying process (3).

Load Rate

The rate of load application for the standard ASTM test for determining compressive strength perpendicular to the grain is a constant strain rate of 0.6 pct/min (4). When the rate of load application is faster, higher stress levels, as a function of strain, are observed, and lower stress levels are observed when the rate is slower, as shown in figure 8 (3).

Creep and Relaxation

Creep is the continuation of deformation after a static load is applied. In wood specimens, this deformation can

continue for a period of years. The deformation due to creep can be expected to be less than, or equal to, the initial deformation caused by the load application. Since deformation continues after the load is applied, failure can occur at very low stress levels. This failure phenomenon is called duration of stress (3).

The opposite of creep is relaxation. Relaxation is the reduction in stress after an applied displacement. Owing

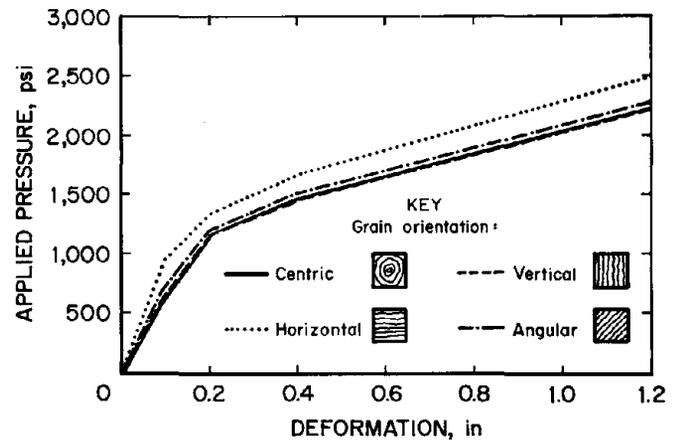


Figure 7.—Effect of grain orientation on wood strength.

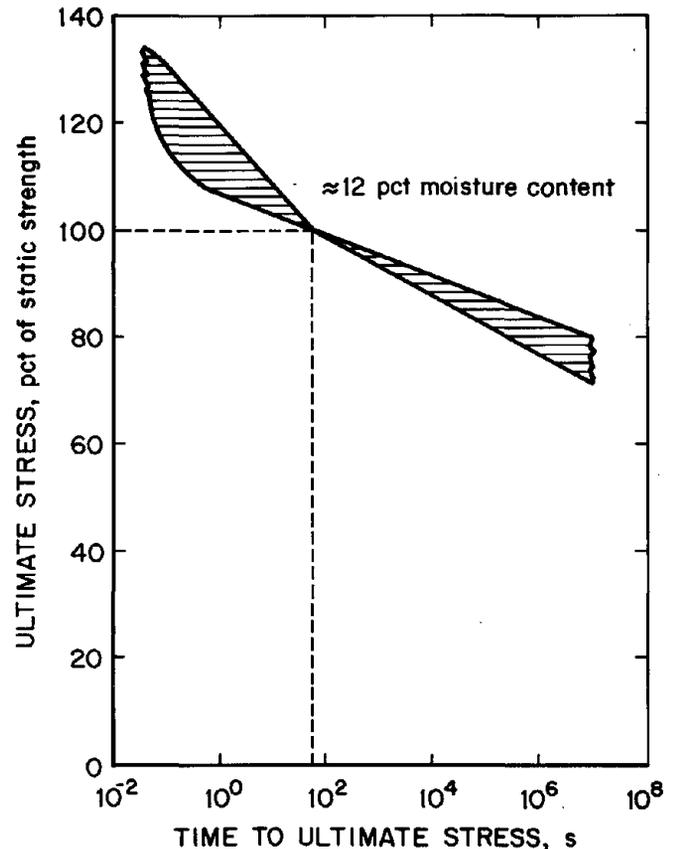


Figure 8.—Effect of load rate on wood strength.

to relaxation, the force required to deform a specimen is higher than the force required to maintain the deformation (3). Therefore, when a wood specimen is deformed by an applied displacement, the resistance provided by the wood will decrease with time.

Load Conditions

The ASTM standardized test for determining the strength of wood is illustrated in figure 4. A 2- by 2- by 6-in block was loaded on a 4-in² area on the center of the top surface of the block. Variations from this standardized ASTM test reduce the measured strength of the wood. Factors that affect these strength determinations are (1) the distance from where the load is applied to the end of the specimen; (2) the percentage of specimen area that is loaded; and (3) the overall size of the specimen. The effects of these factors are illustrated in figure 9 and analyzed in detail as follows.

Areas of unstressed wood adjacent to the loaded area of a wood specimen contribute to its strength. It has been shown that the stress is distributed from the edge of the loaded area to a distance 1.5 times the thickness of the specimen (7). When the loaded area is moved closer to the end of the specimen, the full benefit of the unstressed wood is lost, and the strength of the wood is diminished.

Likewise, when a larger percentage of the area of the specimen is loaded, the strength of the wood is reduced. This condition is similar to the end effect in that less volume of unstressed wood occurs, resulting in lower stress levels. When the full surface of the specimen is loaded, the resulting stress is lowest because no unstressed areas exist to contribute to the strength of the adjacent stressed areas. This phenomenon also occurs when the load is applied to multiple contacts without sufficient distance between them.

Finally, the size of the specimen affects the results of the tests for compressive strength perpendicular to the grain. Shrinkage stresses increase as the size of the specimen increase, resulting in more and larger defects that reduce the strength of the wood.

FACTORS TO CONSIDER IN WOOD-CRIB CONSTRUCTION

The performance of a wood crib is dependent on the material properties of the wood and the construction configuration (8). Some construction parameters can be controlled while others cannot.

Type of Wood

The capacity and stiffness of a crib is largely dependent upon the type of wood used in the crib construction.

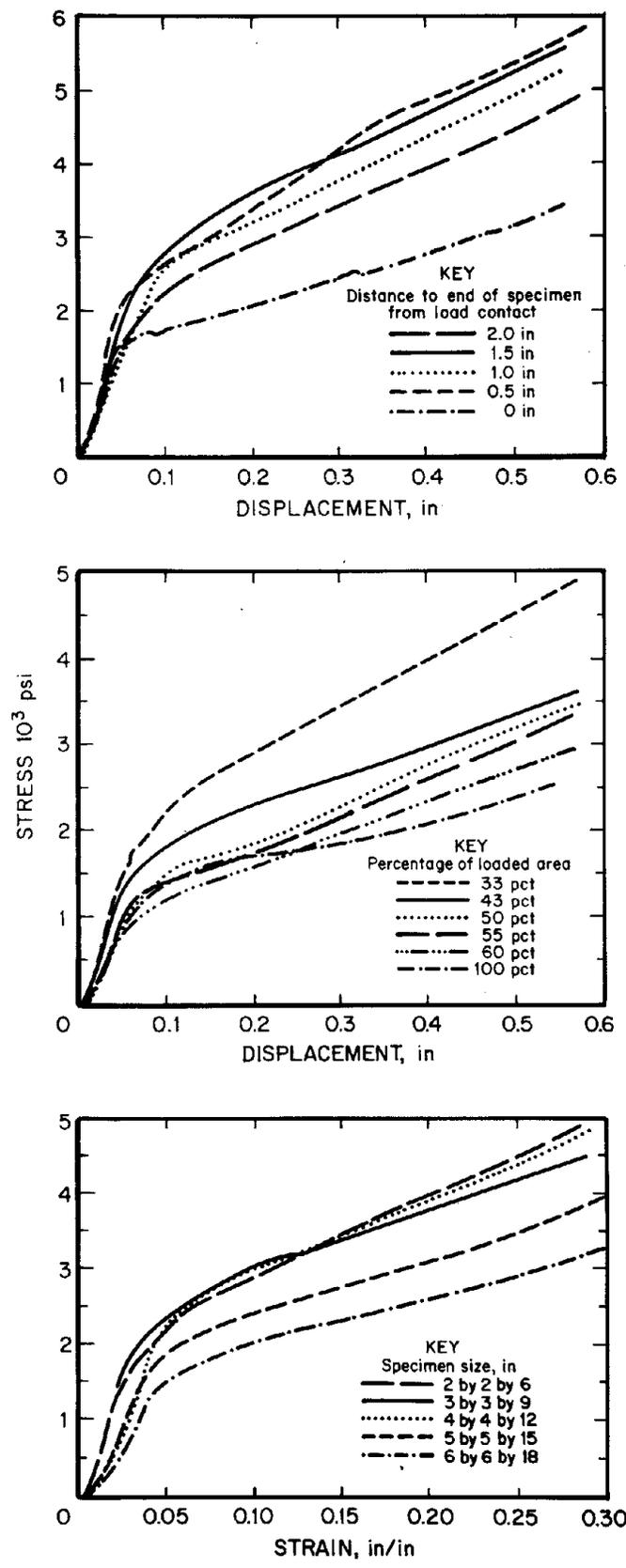


Figure 9.—Effect of load conditions on determining strength of wood.

Table 1 documents the compressive strength and hardness of common wood species used for crib construction. Higher strength wood provides proportionally greater capacity and stiffness. Since crib response is determined by the weakest timber, cribs should be constructed from wood of the same species or similar compressive strength and hardness.

Table 1.—Mechanical properties of common wood species

| Wood species | Compressive strength, ¹ psi | Average hardness, ² lb |
|-----------------------------------------|----------------------------------------|-----------------------------------|
| Hardwood: | | |
| Yellow birch ³ | 723 | 1,020 |
| Rock elm | 1,012 | 1,130 |
| Black locust | 1,886 | 1,635 |
| Black maple ³ | 997 | 1,010 |
| Red maple | 686 | 825 |
| Northern red oak ³ | 987 | 1,145 |
| Pin oak | 1,179 | 1,290 |
| White oak | 1,109 | 1,210 |
| Yellow poplar | 470 | 490 |
| Softwood: | | |
| Douglas fir | 773 | 585 |
| Western larch | 867 | 670 |
| Jack pine | 575 | 485 |
| Lodgepole pine ³ | 443 | 405 |
| Ponderosa pine | 597 | 390 |
| Tamarack | 699 | 485 |

¹Unseasoned wood specimen at 0.04 inches of displacement.

²Average of dry and unseasoned values.

³Species used for development of predictive model.

Timber Dimensions

An important consideration for crib construction is the width of the timber since this dimension determines the contact area and the capacity of the crib. Timber cross sections can be cut in a square, with the height the same as the width, or in a rectangle, with the height less than the width. Maximum capacity is attained when the timbers are stacked to maximize the interlayer contact area (fig. 10). The placement of just a single layer of timbers with the smaller dimension in contact with the adjacent layers reduces the crib stiffness by reducing the contact area and degrades stability by reducing the moment of inertia. The use of planks or header boards that are at least as wide as the timbers is the best solution to close the gap between the last layer of timbers and the mine roof. This should be done before wedges are installed to tighten the crib against the mine roof and floor.

The length of the timber is another important consideration. The aspect ratio is the height of the crib divided by the distance between the contact centers at the corners of the crib structure, as shown in figure 11. Hence, the aspect ratio decreases as the timber length increases or as

the mining height decreases. Increasing the length of the timbers also increases the moment of inertia of the structure. The effect of decreasing the aspect ratio by increasing the timber length is depicted in figure 12. In general, a reduction in the aspect ratio or an increase in the moment of inertia through the use of longer timbers increases the stability of the crib structure by increasing its resistance to buckling. This increase in stability provides higher crib resistance per unit of roof-and-floor convergence.

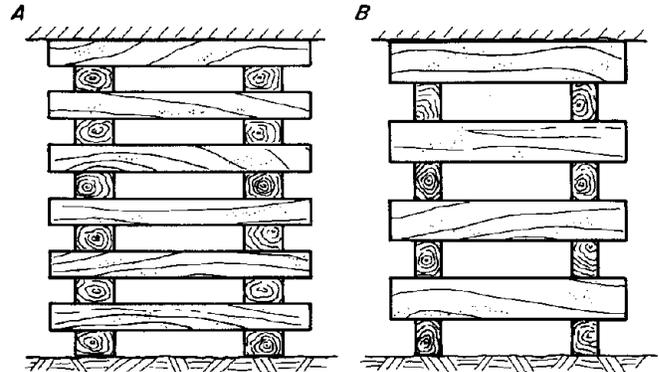


Figure 10.—Placement of timbers with rectangular cross sections (A, Wide side down; B, wide side up).

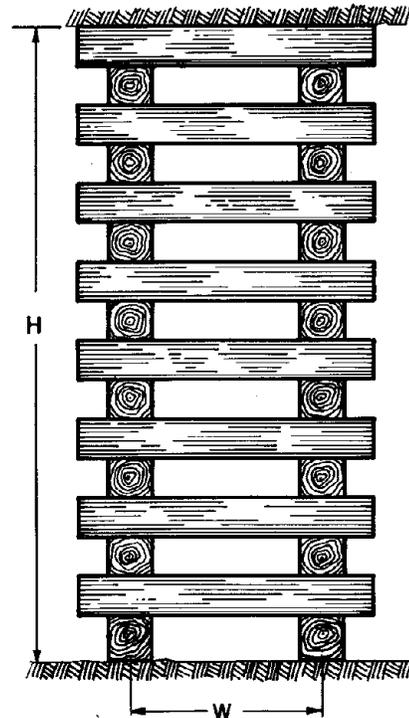


Figure 11.—Aspect ratio for wood-crib structures.

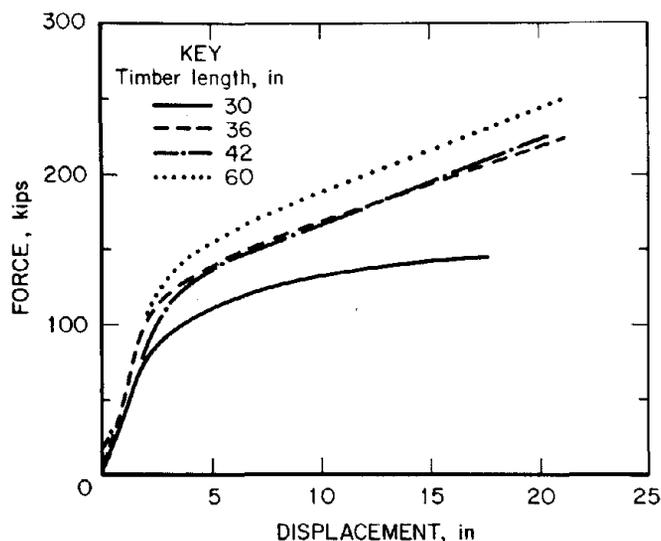


Figure 12.—Effect of increasing timber length on crib performance.

Mining Height

The height of the crib is dictated by the height of the coal seam, but the height effect can be minimized by controlling the aspect ratio of the crib to maintain the desired crib stiffness and stability. Figure 12 shows the effects of timber lengths ranging from 30 to 60 in on the performance of an 80-in-high 2×2 crib. It is recommended that the aspect ratio be less than 5.0 to provide stable crib performance through 20-pct strain. Some decrease in capacity can be expected during plastic deformation when the aspect ratio exceeds 4.3, but the crib will remain stable through an aspect ratio of 5.0. Cribs constructed with aspect ratios less than 2.5 consume more wood than is necessary to provide effective roof support.

Overhanging Construction

Wood cribs constructed with overhanging timbers as shown in figure 11 perform better than cribs constructed without overhanging timbers. The improved performance of the overhanging timber construction primarily is due to end effects. When the load is applied to the end of the timber, the strength of the timber and stiffness of the crib structure is lower. Crib constructions without overhanging timbers are susceptible to local shear failures of the individual timbers (fig. 13), which create unequal loading at the weakened layer and contribute to the buckling of the



Figure 13.—Shear failure of timber in crib constructed without overhanging timbers.

crib structure. Overhanging timbers interlock during convergence and reduce the effects of shear failures on the individual timbers. Figure 14 compares two cribs constructed with 36-in timbers, one with overhang and one without. The crib with the overhanging timbers developed about 10 pct more resistance to an applied displacement than the crib without overhanging ends. An overhang length of one-half the width of the timber is recommended (fig. 15) to optimize the overhang benefits given the disadvantages of increasing the aspect ratio.

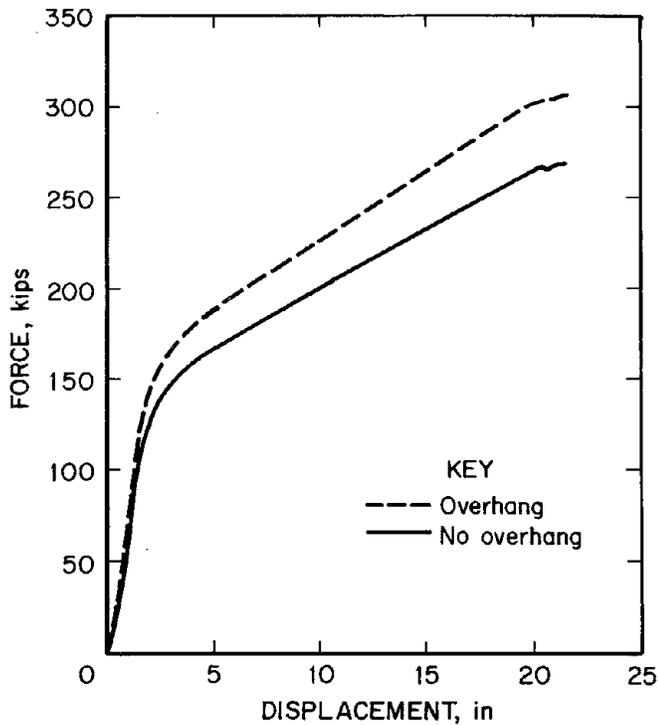


Figure 14.—Comparison of crib performance with and without overhanging timber construction.

Number of Timbers Per Layer

The number of contact points in a crib construction equals the square of the number of timbers per layer. Theoretically, the resulting increase in contact area (fig. 16) proportionally increases the capacity and the stiffness of the crib. However, a slight reduction in timber strength and stiffness from this theoretical expectation is realized in multitimbered crib constructions due to the increase in the percentage of the loaded area and the effect of the aspect ratio on crib stability.

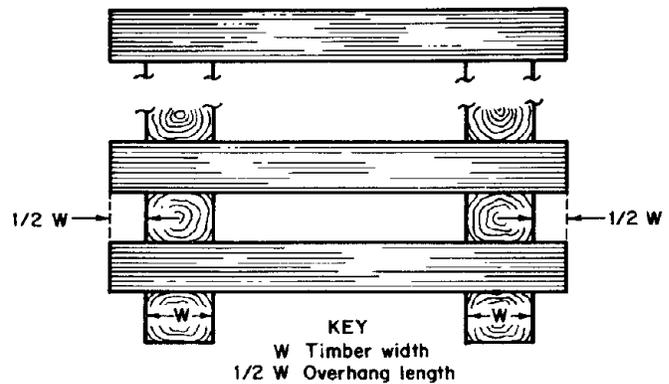


Figure 15.—Overhanging timber construction for wood cribs.

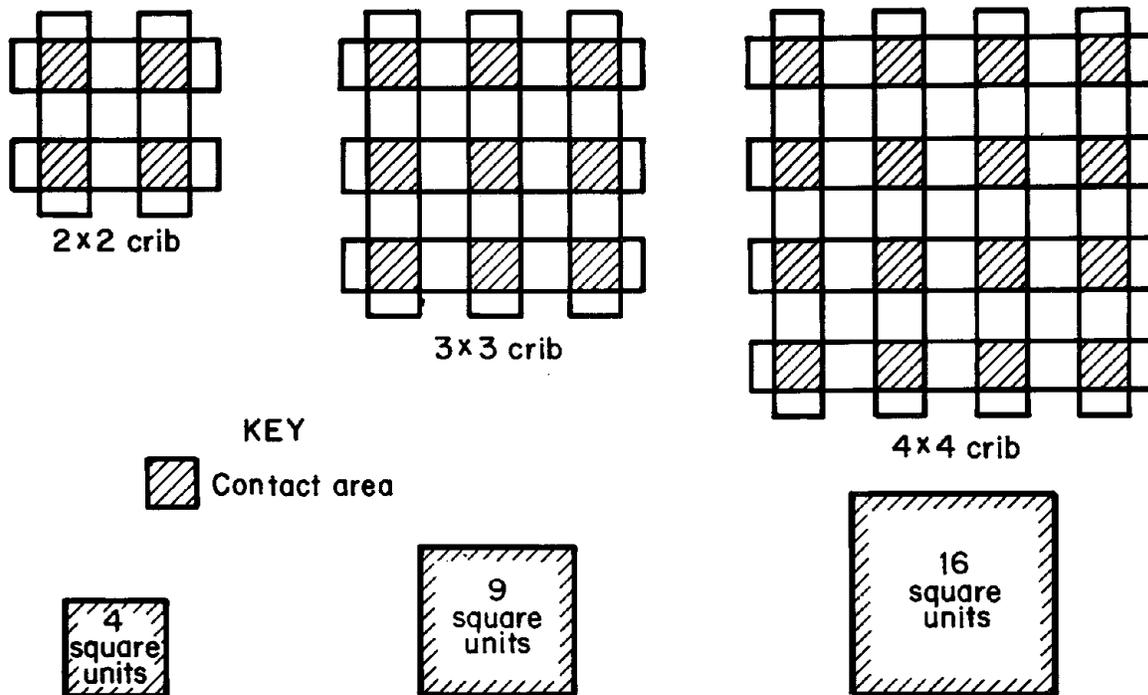


Figure 16.—Increases in contact area due to increase in number of timbers per layer.

WOOD-CRIB PERFORMANCE MODEL

Using the data collected from more than 100 tests of full-size cribs and more than 100 tests of small wood specimens, a model to predict the force-displacement behavior of various crib designs was developed. Three species of hardwoods and one softwood species are represented in the data. Each test specimen was constructed using timbers of the same wood species.

The characteristic equation developed in the model to predict the load-displacement behavior of wood cribs is shown in equation 1. The compressive strength perpendicular to the grain and the hardness of the wood species are the foundation of the model. The compressive strength coefficient (A) and the exponential term of the equation represent the capacity of the crib during the linear elastic phase of deformation. The linear elastic crib performance is also dependent on the height of the structure, as represented by the height factor (HTFCT) in the exponential term of the equation. The plastic stiffness coefficient (K_p) predicts the performance of the structure during the linear plastic phase of deformation. The plastic stiffness coefficient is based on the hardness of the wood species. Adjustments in crib performance also include factors pertaining to (1) the percentage of timber contact area (PCTFCT); (2) the aspect ratio of the crib structure (ARFCT); and (3) construction with or without overhanging timbers (OHFCT).

$$F_{\text{Crib}} = A \times \text{OHFCT} \times \text{PCTFCT} \times \left(1 - e^{-(\text{HTFCT}) \times (\delta)}\right) + \text{PCTFCT} \times \text{ARFCT} \times K_p \times \delta, \quad (1)$$

where F_{Crib} = crib resistance, kips,

A = compressive strength coefficient, kips,

K_p = plastic stiffness coefficient, kips/in,

δ = displacement, in,

OHFCT = overhanging timber factor,

HTFCT = height factor,

PCTFCT = percentage of contact area factor,

and ARFCT = aspect ratio factor.

The information required to apply the model is as follows: (1) the species of the wood; (2) the compressive

strength and hardness of the wood; (3) the dimensions of the timbers; (4) the number of layers in the structure; (5) the number of timbers per layer; and (6) whether the crib is to be constructed with or without overhanging timbers. The construction of wood cribs without overhanging timbers is not recommended since the compressive strength of the wood is reduced and the crib structure is more susceptible to buckling from the local failure of individual timbers.

Data on the compressive strength and hardness of several species of wood are reported by the Forest Service of the U.S. Department of Agriculture and the ASTM (3). Compressive strength and hardness values for wood species commonly used for mine timbers are listed in table 1. The compressive strengths as reported in table 1 are determined at 0.04 in of displacement on wood specimens with a moisture content greater than 12 pct. Note that the 0.04 in of displacement is in reference to the ASTM material test on a 2- by 2- by 6-in wood specimen, and is in no way related to roof-and-floor convergence or crib displacement. If species of wood other than those listed in table 1 are used, and only the stress at the proportional limit is available, then the compressive strength at 0.04 in of displacement can be calculated from equation 2.

$$CS_{0.04} = 1.589 \times CS_{PL} + 42.44, \quad (2)$$

where $CS_{0.04}$ = compressive strength at 0.04 in of displacement, psi,

and CS_{PL} = compressive strength at the proportional limit, psi.

METHODOLOGY FOR MODEL UTILIZATION

Application of the model is a step-by-step process described by the flow chart shown in figure 17 and described in steps 1 through 7 below. An example is provided in appendix A where the force-displacement relationship of a 3×3 wood crib is determined by the wood-crib performance model. A comparison of the model's force-displacement prediction to the measured crib response from full-scale testing in the USBM's Mine Roof Simulator is shown in figure 18.

1. Determine the interlayer contact area by multiplying the area per contact by the number of contacts per layer. The area per contact generally equals the square of the width of the timber, and the number of contacts per layer equals the square of the number of timbers per layer.

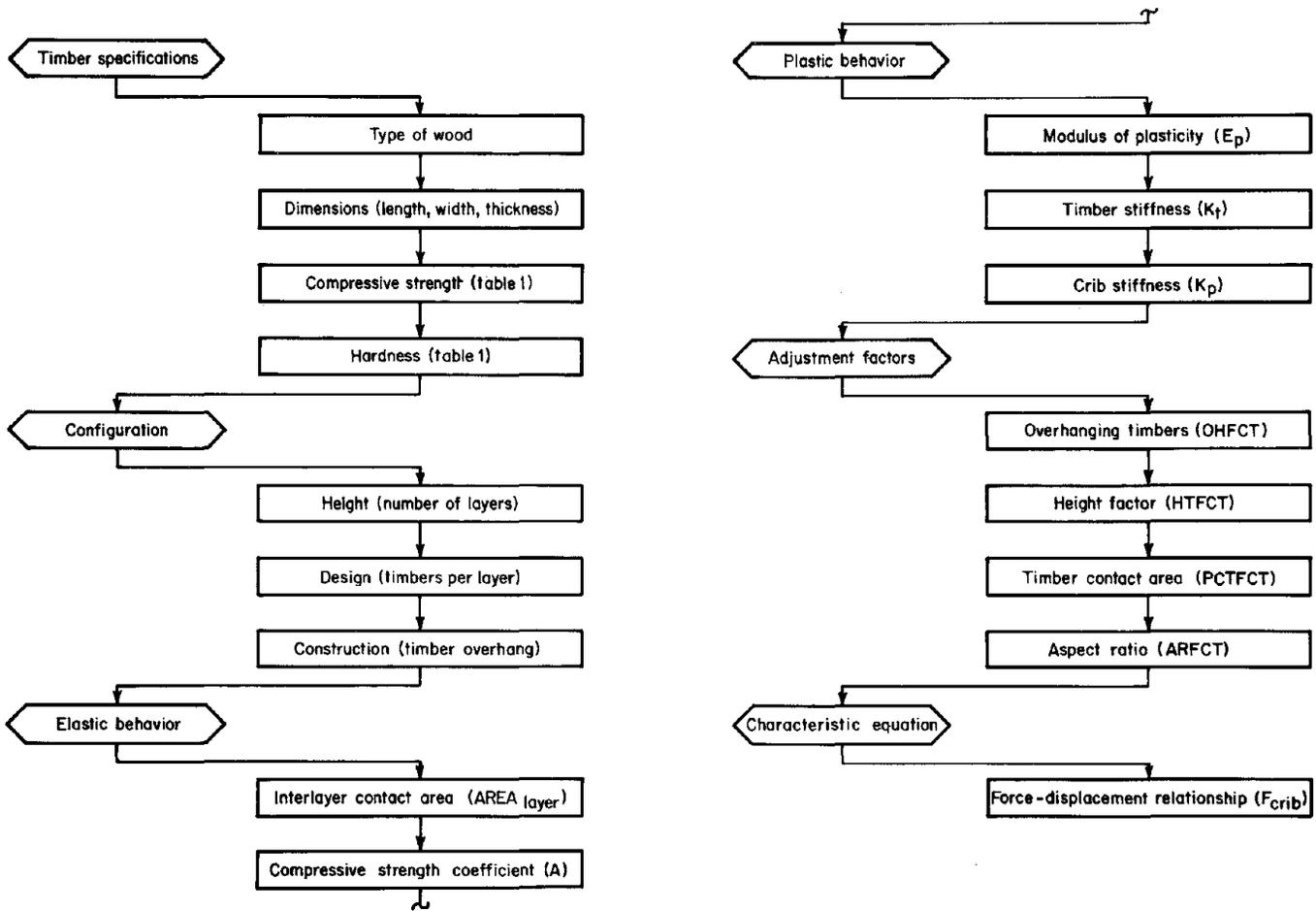


Figure 17.—Flow chart for application of wood-crib model.

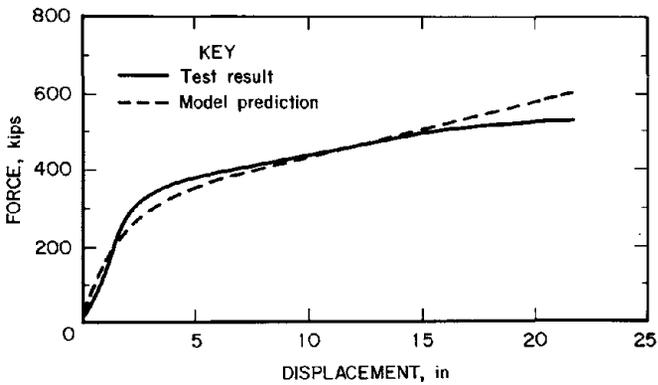


Figure 18.—Comparison of wood-crib model prediction to measured wood-crib response from testing in the USBM'S Mine Roof Simulator.

$$AREA_{Layer} = AREA_{Contact} \times CONTACTS, \quad (3)$$

where $AREA_{Layer}$ = interlayer contact area, in^2 ,

$$AREA_{Contact} = \text{area per contact, } in^2,$$

and $CONTACTS$ = number of contacts per layer.

2. Multiply the interlayer contact area by the compressive strength of the wood species to determine the compressive strength coefficient.

$$A = STRENGTH \times AREA_{Layer} \times 10^{-3}, \quad (4)$$

where A = compressive strength coefficient, kips,

$STRENGTH$ = compressive strength of wood, psi,

and $AREA_{Layer}$ = interlayer contact area, in^2 .

3. Determine the modulus of plasticity for the wood using the wood hardness (table 1) in equation 5a or 5b, depending on the overhang condition.

$$E_p = 4.63 \times HARDNESS - 1,060, \quad (\text{with overhang}), \quad (5a)$$

and $E_p = 4.45 \times \text{HARDNESS}$
 $- 1,400$, (without overhang), (5b)

where E_p = modulus of plasticity, psi,

and HARDNESS = wood hardness, lb.

4. Determine the plastic stiffness of a single timber by multiplying the area of a single interlayer contact by the modulus of plasticity and dividing by the timber thickness.

$$K_t = \frac{E_p \times \text{AREA}}{\text{THICKNESS}} \times 10^{-3}, \quad (6)$$

where K_t = plastic stiffness of mine timber, kips/in,

E_p = modulus of plasticity of mine timber, psi,

AREA = area per contact, in²,

and THICKNESS = timber thickness, in.

5. Determine the stiffness of the crib structure during plastic deformation by multiplying the number of contacts per layer by the timber stiffness and dividing by the number of layers as described in equation 7. The number of contacts per layer equals the square of the number of timbers per layer.

$$K_p = \frac{K_t \times \text{CONTACTS}}{\text{LAYERS}}, \quad (7)$$

where K_p = stiffness of crib structure during plastic deformation, kips/in,

K_t = plastic timber stiffness, kips/in,

CONTACTS = number of contacts per layer,

and LAYERS = number of layers in crib.

6. Determine the adjustment factors for height, percentage of timber contact area, aspect ratio, and construction without overhanging timbers. These factors reduce the performance of the crib when certain thresholds are exceeded as described below. A value of 1.0 is used when crib performance is not affected significantly by these parameters:

height factor (HTFCT),

$$\text{HTFCT} = 1.62 - 0.0117 \times \text{Crib Height}, \quad (8)$$

percentage of timber contact area factor (PCTFCT),

$$\text{PCTFCT} = 0.9 \text{ when } \text{AREA}_{\text{pct}} \geq 55, \quad (9a)$$

$$\text{PCTFCT} = 1 \text{ when } \text{AREA}_{\text{pct}} < 55, \quad (9b)$$

$$\text{AREA}_{\text{pct}} = \frac{\frac{\text{AREA}_{\text{Layer}}}{\text{CONTACTS}} \times \text{TIMBERS}}{\text{TW} \times \text{TL}} \times 100, \quad (10a)$$

$$\text{and } \text{AREA}_{\text{pct}} = \frac{\text{TW} \times \text{TIMBERS}}{\text{TL}} \times 100, \quad (10b)$$

where AREA_{pct} = percent of timber contact area, pct,

$\text{AREA}_{\text{Layer}}$ = interlayer contact area, in²,

CONTACTS = number of contacts per layer,

TIMBERS = number of timbers per layer,

TW = timber width, in,

and TL = timber length, in;

aspect ratio factor (ARFCT),

$$\text{ARFCT} = 2.41$$

$$- (0.33 \times \text{AR}) \text{ when } \text{AR} \geq 4.3, \quad (11a)$$

$$\text{ARFCT} = 1 \text{ when } \text{AR} < 4.3, \quad (11b)$$

$$\text{and } \text{AR} = \frac{\text{HEIGHT}}{\text{TL} - 2 \times (\text{Overhang}) - \text{TW}}, \quad (12)$$

where AR = aspect ratio,

HEIGHT = height of crib, in,

OVERHANG = overhang distance, in,

TL = timber length, in,

and TW = timber width, in;

and overhanging timber construction factor (OHFCT),

$$\text{OHFCT} = 0.9$$

when construction is without overhanging
timbers, (13a)

and OHFCT = 1

when construction is with overhanging
timbers. (13b)

7. The crib force-displacement relationship is determined using equation 1.

$$F_{\text{Crib}} = A \times \text{OHFCT} \times \text{PCTFCT} \times 1 - e^{-(\text{HTFCT}) \times (\delta)} \\ + \text{PCTFCT} \times \text{ARFCT} \times K_p \times \delta,$$

where F_{Crib} = crib resistance, kips,

A = compressive strength coefficient, kips,

K_p = plastic stiffness coefficient, kips/in,

δ = displacement, in,

HTFCT = height factor,

OHFCT = overhanging timber factor,

PCTFCT = percentage of contact area factor,

and ARFCT = aspect ratio factor.

MODEL LIMITATIONS

The variables that were controlled during the development of the model were the loading rate, the species of the wood, the length of the timbers, the height of the structure, whether the crib was constructed with overhanging timbers, and the number of timbers per layer. When all of these parameters are known, the force-displacement relationship of most crib designs can be predicted to within a 10-pct error. Limitations of the model concerning these and other parameters require consideration.

Mixed Species

The consequences of using a mixture of different species of wood in constructing a crib have not been evaluated fully. When mixed species of wood are used, it is recommended that the model using the values that represent the lowest compressive strength and hardness of the wood species used in the construction be applied. This approach will provide a conservative estimate of crib performance. Since the use of wood of different species can cause increased susceptibility to buckling, a lower aspect ratio at which the model should be derated may also be used, but further research is needed to quantify this limitation.

Configuration Limitations

The model is limited to stacked timber configurations as shown in figure 1. The configuration is also limited relative to the length of the timbers and the height of the structure. The length of the timbers and the height of the crib interact to affect the overall stability of the structure. The length of the timbers ranged from 30 to 60 in and the height ranged from 50 to 110 in. The aspect ratios calculated from these combinations of crib heights and timber lengths ranged from 1.67 to 6.11. Adjustments are made in the model for aspect ratios greater than 4.3. Construction of cribs with aspect ratios greater than 5.0 is not recommended.

Construction of cribs without overhanging timbers also is not recommended. If the model is applied to cribs constructed without overhanging timbers, the adjustment factor described in the model should be used. A lower aspect ratio in which crib performance is degraded also may be applied, but further research is needed to quantify this limitation.

Load Application

The behavior of wood in compression perpendicular to the grain varies depending on the rate and nature of the load application. The model was developed under a displacement controlled load environment in which a constant rate of displacement of 0.5 in/min was applied to the crib structure. Since wood has time-dependent properties, the rate of load application can affect significantly the response of wood cribs. Tests on full-scale cribs at 0.05 in/min showed little difference from tests conducted at 0.5 in/min. However, underground convergence rates in coal mines of 0.01 in/h or 0.00017 in/min have been associated with unstable roof conditions. Load application rates on this order may diminish the resistance provided by wood-crib supports by 20 to 30 pct (δ).

The crib structure is also affected by creep. Creep is the continuation of crib displacement after an applied force. The rate of creep is a function of the load on the structure. When the force acting on the crib produces a crib response in the elastic deformation phase, the rate of creep is very slow. When the crib response is in the range of plastic deformation, the creep rate accelerates rapidly as shown in figure 19. Tests of wood cribs to quantify creep show that the model can be used to predict the initial displacement that is required to produce a resistive force by the crib (fig. 20). After the force is applied, creep will allow the displacement to continue to a value of twice the initial displacement.

When a displacement is applied to a wood crib, the resistive force reacted by the crib due to the displacement can also be predicted by the model. Relaxation of the wood causes the crib resistance to be reduced by approximately 30 pct after just 1 h, and 50 pct after 48 h (fig. 21).

Nonlinear Behavior

Another limitation is that the model does not predict nonlinear plastic behavior. The linear term of the

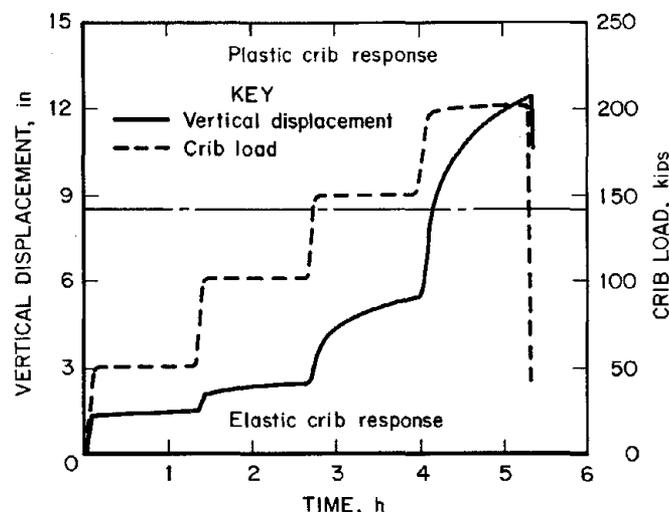


Figure 19.—Acceleration of creep rate during plastic wood behavior.

equation describes only the linear plastic deformation of the crib. For typical crib configurations, plastic deformation will become nonlinear at strains between 20 and 30 pct, depending upon the moment of inertia and the aspect ratio of the structure. In general, nonlinear plastic behavior will begin sooner if the moment of inertia is increased or if the aspect ratio is reduced. The model will maintain the 10-pct error limit through 20-pct strain if the aspect ratio is between 1.7 and 6.1.

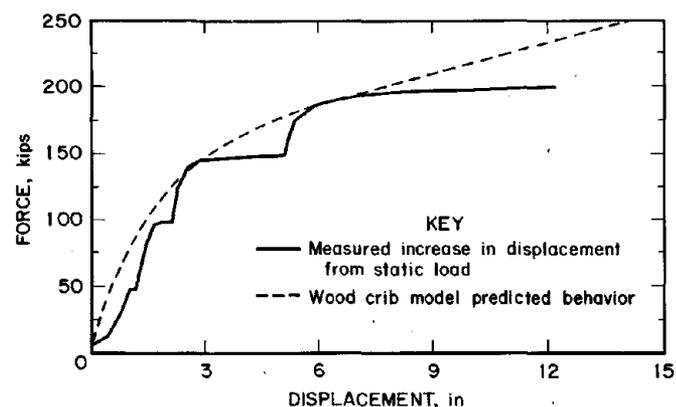


Figure 20.—Capability of wood-crib model to predict crib response from creep.

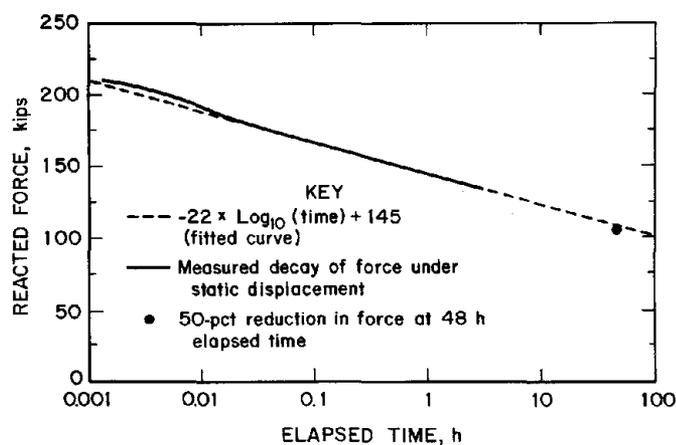


Figure 21.—Crib resistance in relation to relaxation of wood after an applied displacement.

EMPLOYMENT STRATEGIES

Design and employment of a crib support system requires the identification of the load conditions imposed by the mine strata and knowledge of the performance of the crib structure. The wood-crib performance model previously presented provides information on the performance of crib designs. Determining the load conditions imposed by the mine environment is often the most difficult part of the process because of the complex behavior of the roof-and-floor strata. Actual mine experience relating to immediate roof-and-floor stability provides valuable insight into determining the design requirements for the crib support system. Analytical models of roof behavior that can be used to quantify load conditions and support design requirements also are described. These models should be applied only with consideration of their limitations in describing the complex ground behavior.

DESIGN AND EMPLOYMENT CRITERIA

The primary goal in crib design and employment is to provide a support system, consisting of an arrangement of cribs of a particular design, that will resist the anticipated loading imposed by the strata within a displacement that preserves the integrity of the immediate roof in the mine opening. More specifically, the design requirements are summarized as follows:

1. *Crib stiffness.*—The crib should be designed with a stiffness that will prevent failure of the immediate roof. Roof failure is caused generally by delamination of roof layers or excessive roof sag.

2. *Maximum crib capacity.*—As a safeguard, the crib should have sufficient capacity and stability to support the weight of any unstable strata that are detached unintentionally from stable roof structures. This capacity must be developed within a displacement (allowable entry closure) that will provide an opening to maintain ventilation and entry accessibility without endangering the safety of the miners.

3. *Crib stability.*—The crib should be able to provide the required resistance to maintain roof control without loss of stability through a displacement that includes the sum of the roof deflection, pillar deformation, and floor heave.

4. *Roof-and-floor contact pressures.*—The crib should have adequate contact area to provide roof-and-floor contact pressures that are compatible with the strength of the immediate roof and floor.

5. *Crib spacing and employment cost.*—The cost of the support system will depend largely on how far apart the cribs can be spaced. The crib spacing is determined by the stiffness of the cribs in relation to the load required to produce deflection of the roof to failure. The spacing is limited by the capacity of the crib to support the weight of

a detached rock mass within a displacement that will not compromise safe passage or ventilation of the mine entry, and by the capability of the roof to span without support.

Crib Stiffness

A goal of ground control and support design is to provide sufficient support to prevent roof failure. A theoretical determination of roof failure is difficult since the conditions that produce roof failure are complex. Analytical solutions to roof behavior mechanics generally assume that the immediate roof acts as a beam, and structural beam mechanics are used to compute critical loading and deflection that produce failure of the beam through bending. Application of this theory requires knowledge of (1) the beam length; (2) the tensile strength of the roof rock; (3) the modulus of elasticity of the roof rock; and (4) the thickness of the roof beam. Equations to determine critical roof beam loading and deflection are summarized as follows. To facilitate determination of crib spacing, loading is expressed as per foot of entry development.

The maximum deflection of the immediate roof beam will occur at the center of the opening and can be determined from equation 15a for a fixed-end condition, or equation 15b for a pinned-end condition (11). A fixed-end condition applies if it is assumed that the roof is clamped rigidly at its ends by the overburden pressures and the resistance provided by the coal pillars. Since the coal is likely to deform, a more reasonable approach may be to assume a pinned-end condition where some roof rotation over the pillar is permitted. A practical estimate for the beam length is the width of the entry plus the width of the yield zone in the adjacent coal pillars as illustrated in figure 22 and described in equation 14. The width of the yield zone, which is a function of the depth of cover and seam height, can be determined from figure 23 using Wilson's analysis.⁵

$$L = W + Y_{P1} + Y_{P2}, \quad (14)$$

where L = length of roof beam, ft,
 W = width of the opening, ft,
 Y_{P1} = yield zone for pillar 1, ft,
 and Y_{P2} = yield zone for pillar 2, ft.

⁵Information on Wilson's analysis from Mark, C., "The Wilson Approach to Estimating Coal Strength." BuMines internal report, 1987.

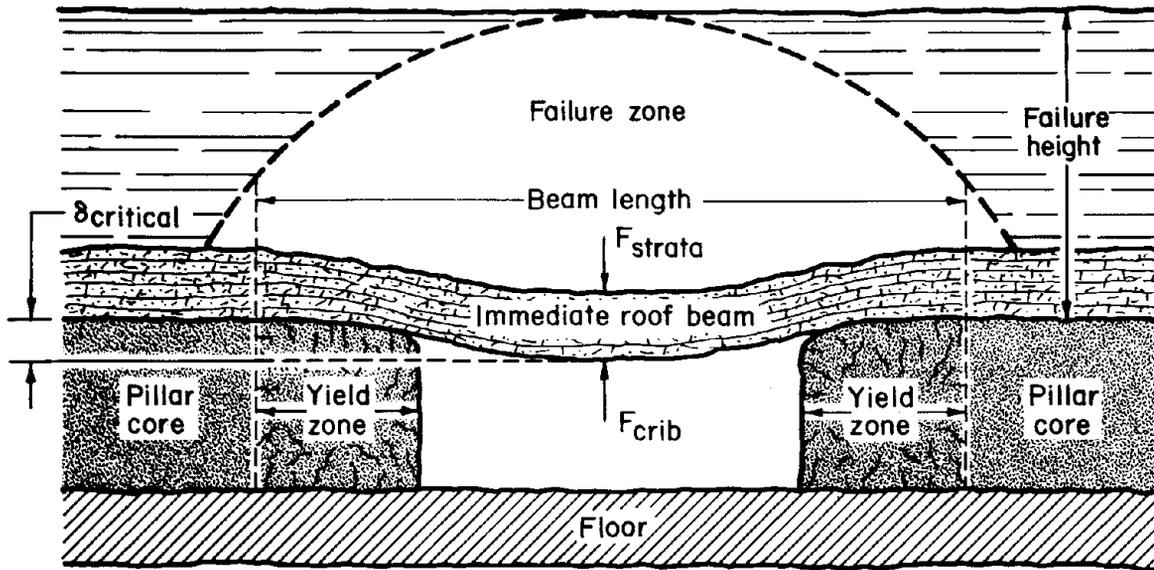


Figure 22.—Estimation of beam length for analysis of roof displacements.

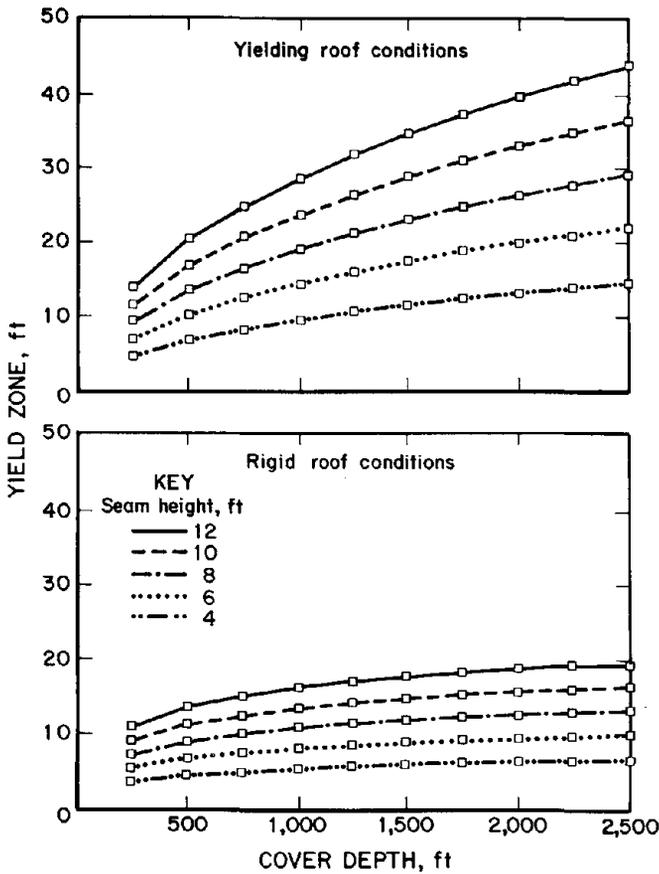


Figure 23.—Width of yield zone in coal pillars.

$$\delta_{critical} = \frac{\sigma \times L^2}{16 \times E \times t}, \text{ fixed-end,} \quad (15a)$$

and
$$\delta_{critical} = \frac{5 \times \sigma \times L^2}{24 \times E \times t}, \text{ pinned-end,} \quad (15b)$$

where $\delta_{critical}$ = critical displacement of roof beam, in,

σ = tensile strength of the roof rock, psi,

L = length of roof beam, in,

E = modulus of elasticity of roof rock, psi,

and t = thickness of immediate roof beam, in.

The load required to deflect the roof beam to failure can be determined from equation 16a for fixed-end conditions, and equation 16b for pinned-end conditions.

$$F_{Critical} = \frac{2 \times t^2 \times \sigma}{L} \times 12 \times 10^{-3}, \text{ fixed-end,} \quad (16a)$$

and

$$F_{Critical} = \frac{4 \times t^2 \times \sigma}{3 \times L} \times 12 \times 10^{-3}, \text{ pinned-end,} \quad (16b)$$

where F_{Critical} = critical loading of the roof beam, kips/ft,

t = beam thickness, in,

σ = tensile strength of roof rock, psi,

and L = length of roof beam, in.

The resultant force acting on the immediate roof beam must be less than the critical beam load to prevent deflection of the beam to failure. This requirement is expressed in equation 17, where the resultant force is expressed as the difference between the strata load and the crib resistance. In order for the crib support system to prevent roof failure, it is required that the cribs develop sufficient capacity to offset the imposed strata loading to maintain a resultant force that will prevent deflection of the beam to failure (see figure 22).

$$F_{\text{Roof}} - F_{\text{Supsys}} < F_{\text{Critical}} \quad (17)$$

where F_{Supsys} = crib resistance, kips/ft,

F_{Roof} = imposed strata loading, kips/ft,

and F_{Critical} = critical beam loading, kips/ft.

Strata loading is determined by estimating a failure height in which the near-seam roof separates from the stable strata above, and then computing the weight of this detached rock mass. Failure heights can be estimated by identifying a parting plane where separation above the roof-bolted zone is likely to occur. Unal relates the failure height of the coal mine roof to the quality of the roof strata using the Rock Quality Index (RMR) as described in equation 18 (10). Unal's equation indicates that the failure height ranges theoretically from a lower limit of 0 for very competent rock (RMR = 100) to an upper limit equal to the width of the opening for incompetent rock (RMR = 0). Figure 24 depicts failure heights as a function of entry width for RMR ranging from 0 to 80.

$$h = \frac{(100 - \text{RMR})}{100} \times w, \quad (18)$$

where h = failure height, ft,

RMR = rock mass rating,

and w = width of the opening, ft.

The volume of unstable rock that must be supported by the crib system depends on the propagation of roof failure

and the failure height. In the worst case, it can be assumed that the strata will shear at the boundaries of the opening and the entire block then must be supported as shown in figure 25. The weight of this rock mass can be determined using equation 19.

$$F_{\text{Roof}} = w \times h \times \gamma \times 10^{-3}, \quad (19)$$

where F_{Roof} = weight of rock mass per lineal foot, kips/ft,

w = width of the opening, ft,

h = distance from coal seam to parting plane, ft,

and γ = rock density, lb/ft³.

It is more likely that the roof strata will form an arch during failure as depicted in figure 26, where the weight of material within the pressure arch must be supported by the crib support system. The height of the arch has been shown to correlate to the vertical and horizontal stresses acting in the immediate roof. Peng reports that the failure surface of the pressure arch occurs where the vertical stress equals one-tenth of the overburden stress (9). The height of the failure zone is believed to increase as the in situ horizontal stress increases. Failure heights of 0.5 to 1.5 times the seam height are often assumed for determining the height of the pressure arch. The weight of rock within the arch can be estimated in relation to the width of the entry and the height of the arch (failure height) by the following equation.

$$F_{\text{Roof}} = \frac{1}{2} \times \pi \times \frac{w}{2} \times h \times \gamma \times 10^{-3}, \quad (20)$$

where F_{Roof} = weight of rock within arch per foot of mine entry, kips/ft,

w = width of opening, ft,

h = height of pressure arch, ft,

and γ = rock density, lb/ft³.

A more practical solution for defining crib-stiffness requirements is desirable, since the material and mechanical properties of jointed rock masses are not measured easily and the failure of these structures is more complex than the beam theory can address. The USBM currently is developing a roof-rating system that will quantify the stability of a mine roof. However, more research is needed before support stiffness design requirements can be generated

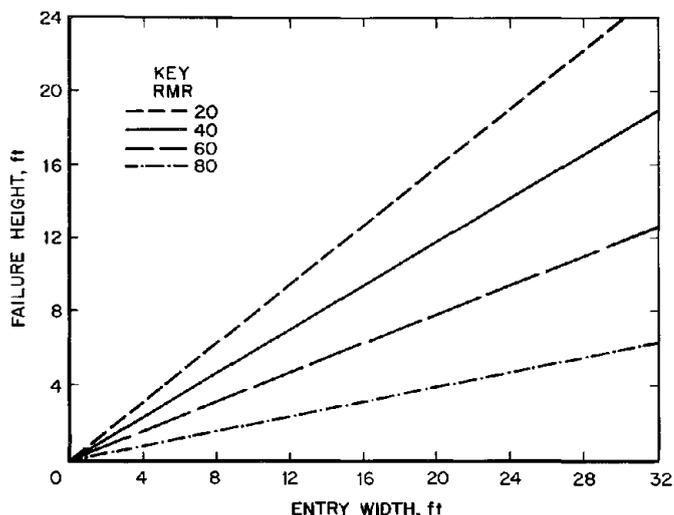


Figure 24.—Roof failure height as a function of entry width and rock mass rating (RMR) for the roof rock.

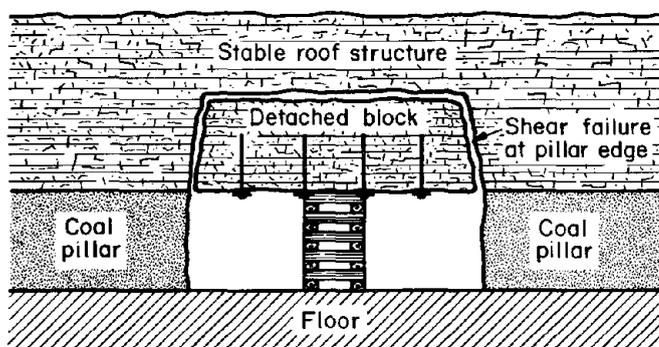


Figure 25.—Detached roof block.

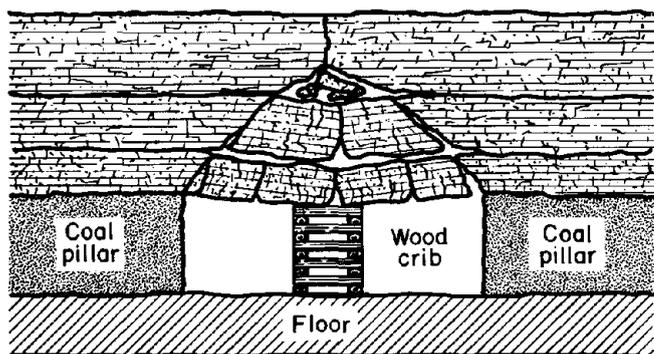


Figure 26.—Crib supporting weight of material within a pressure arch.

from this system. Measures of roof sag and entry closure in relation to roof stability provide valuable information in determining the critical roof deflection and the displacement requirement for the crib stiffness. The imposed

strata loading is more difficult to determine, but an assessment of cavity formations produced by roof falls provides an estimate of the weight of material associated with unstable rock masses.

Maximum Crib Capacity

When the immediate roof has no strength or when the capacity of the immediate roof beam is exceeded ($F_{\text{Critical}} = 0$ in equation 17), then the required crib capacity equals the weight of the detached roof mass as expressed in equation 21. It is required that the crib support system develop sufficient capacity to support the weight of this detached rock mass within a displacement that will preserve an opening to maintain ventilation and entry accessibility. The critical displacement is referred to as the allowable entry closure (δ_{Allow}).

$$F_{\text{Supsys}} (\text{max}) = F_{\text{Roof}}, \quad (21)$$

where $F_{\text{Supsys}} (\text{max})$ = maximum required crib capacity per foot of mine entry, kips/ft,

and F_{Roof} = weight of detached roof mass per foot of mine entry, kips/ft.

Crib Stability

The crib must be able to provide load-carrying capability through a total displacement equal to the sum of the roof beam displacement, pillar deformation, and floor heave as described in equation 22.

$$\delta_{\text{Total}} = \delta_{\text{Roof}} + \delta_{\text{Pillar}} + \delta_{\text{Floor}}, \quad (22)$$

where δ_{Total} = maximum convergence,

δ_{Roof} = displacement of roof beams,

δ_{Pillar} = deformation of pillar,

and δ_{Floor} = floor heave.

Roof beam deflections can be determined from equation 15a or 15b as previously described. The convergence associated with pillar deformation can be estimated from equation 23. Notice that for longwall gate-road systems, the abutment stress must be considered in the analysis.

$$\delta_{\text{Pillar}} = \sigma_V \times \text{ABUT} \times \frac{L}{E}, \quad (23)$$

where δ_{Pillar} = pillar deformation, in,
 σ_V = overburden stress = 1.1 psi per foot of depth,
 ABUT = longwall abutment multiplier, typically 5,
 L = seam height, in,
 and E = coal modulus of elasticity, 250,000 to 500,000 psi.

Another primary source of convergence is floor heave. Floor heave will occur when the pillar loads exceed the strength of the mine floor. The pillars essentially punch into the floor and cause it to buckle upward in the mine entry. Floor heave also may be attributed to horizontal stress that contributes to the buckling of the mine floor. Floor heave can cause problems in crib stability due to the eccentric load conditions imposed by the buckling of the floor strata. The moment of inertia of the crib should be increased by using longer timbers when floor heave causes rotational moments that produce excessive buckling of the crib structure. Crib construction using overhanging timbers also should be used to maximize crib stability for these eccentric load conditions.

Roof-and-Floor Contact Pressures

The roof-and-floor contact pressure developed by the crib support is determined by equation 24. This equation limits the roof-and-floor contact area to twice the interlayer contact area to estimate stress concentrations at areas where the timbers intersect. This approximation of contact area (twice the interlayer contact area) should be replaced by the full timber area whenever the full timber area is the smaller area. This may occur in multitimbered crib constructions with short timbers. The contact pressure should not exceed the bearing capacity of the roof or floor.

$$F_{\text{Psi}} = \frac{F_{\text{Crib}}}{2 \times (\text{TW})^2 \times \text{CONTACTS}} \times 10^3, \quad (24)$$

where F_{Psi} = roof-and-floor contact pressure, psi,
 F_{Crib} = crib resistance at allowable entry closure, kips,
 TW = timber width, in,
 and CONTACTS = number of contacts per layer.

Intuitively, it might be thought that increasing the timber width will reduce the roof-and-floor contact pressures. However, since increasing the timber width also increases the stiffness of the structure, the passive crib support will develop higher forces when wider timbers are employed and the contact pressures may not be reduced. Placing planks of greater width than the crib timbers at the roof-and-floor interface is a better method to reduce roof-and-floor contact pressures. Employing longer timbers will also help, but not in direct proportion to the timber length since the load distribution along the timber is not uniform.

Crib Spacing and Employment Cost

Crib spacing is derived from the stiffness requirement expressed in equation 17 by replacing F_{Support} with the quantity $F_{\text{Crib}}/(\text{spacing} + \text{timber length})$, which represents the crib resistance per foot of mine entry. The solution in simplified form is shown in equation 25. The spacing is defined as the skin-to-skin distance between cribs.

$$\text{SPACE } (\delta_c) = \frac{F_{\text{Crib}} (\delta_{\text{Critical}})}{F_{\text{Roof}} - F_{\text{Critical}}} - \text{TL}, \quad (25)$$

where $\text{SPACE } (\delta_c)$ = crib spacing, ft,

$F_{\text{Crib}} (\delta_{\text{Critical}})$ = capacity of a single crib at the critical roof deflection (δ_{Critical}), kips,

F_{Roof} = imposed strata load as determined from equation 20 or 21, kips/ft,

F_{Critical} = critical beam load as determined from equation 17a or 17b, kips/ft,

and TL = timber length, ft.

The crib spacing is limited by the crib capacity at the allowable entry closure or the capability of the roof to span without support. The spacing limitation imposed by the maximum allowable entry closure is determined from equation 26.

$$\text{SPACE } (\delta_{\text{Allow}}) = \frac{F_{\text{Crib}} (\delta_{\text{Allow}})}{F_{\text{Roof}}} - \text{TL}, \quad (26)$$

where $\text{SPACE } (\delta_{\text{Allow}})$ = spacing limit due to crib capacity at allowable entry closure, ft,

$F_{\text{Crib}} (\delta_{\text{Allow}})$ = crib resistance at allowable entry closure, kips,

F_{Roof} = detached roof load computed from equation 16a or 16b, kips/ft,

and TL = timber length, ft.

The spacing limitation imposed by the unsupported roof span is determined from equation 27. Unsupported roof spans can be determined from equation 28a for fixed-end beam conditions and equation 28b for pinned-end beam conditions, assuming the roof can be modeled by elastic beam behavior. It is recommended that laboratory values of rock strength be degraded by 50 to 75 pct to account for fractures and planes of weakness that exist in full-scale rock masses.

$$\text{SPACE (Span)} = L_{\text{Span}}, \quad (27)$$

where SPACE (Span) = crib spacing limitation due to unsupported roof span, ft,

and L_{Span} = unsupported roof span as determined from equation 28a or 28b, ft.

$$L_{\text{Span}} = \frac{2 \times t^2 \times (\sigma/SF)}{F_{\text{Critical}}}, \text{ fixed-end}, \quad (28a)$$

$$\text{and } L_{\text{Span}} = \frac{4 \times t^2 \times (\sigma/SF)}{3 \times F_{\text{Critical}}}, \text{ pinned-end}, \quad (28b)$$

where L_{Span} = maximum unsupported roof span, ft,

t = thickness of roof beam, in,

σ = tensile strength or modulus of rupture, psi,

F_{Critical} = critical roof beam load as computed from equation 16a or 16b, lb/ft of entry,

and SF = safety factor, 2 to 4 recommended.

The designated crib (SPACING) equals the minimum of (1) the spacing imposed by the crib stiffness and critical roof deflection ($\text{SPACE} (\delta_c)$); (2) the spacing imposed by detached roof load limitation ($\text{SPACE} (\delta_{\text{Allow}})$); and (3) the spacing imposed by the unsupported roof span limitation (SPACE (Span)).

SPACING = Minimum of $\text{SPACE} (\delta_c)$,

$\text{SPACE} (\delta_{\text{Allow}})$,

and SPACE (Span) . (29)

Once the crib spacing is determined, the maximum required crib capacity can be determined from equation 30. This capacity must be developed at a displacement less than or equal to the allowable entry closure (δ_{Allow}).

$$F_{\text{Crib (Max)}} = F_{\text{Roof}} \times (\text{SPACING} + TL), \quad (30)$$

where $F_{\text{Crib (Max)}}$ = maximum required crib capacity, kips,

F_{Roof} = loading due to detached roof load, kips/ft,

SPACING = designated crib spacing, ft,

and TL = timber length, ft.

The employment cost per foot of entry for the crib support system is based on the construction cost per unit crib and the spacing at which the cribs are employed (equation 29). The construction cost represents the material and labor costs required to construct a crib.

$$\text{EMPLOY COST} = \frac{\text{CONS COST}}{\text{SPACING} + TL}, \quad (31)$$

where EMPLOY COST = employment cost, \$/ft of entry,

CONS COST = cost to construct a crib, \$,

SPACING = minimum of $\text{SPACE} (\delta_c)$,
 $\text{SPACE} (\delta_{\text{Allow}})$,
 SPACE (Span) , ft,

and TL = timber length, ft.

The equivalent cost spacing is the spacing that provides the same employment cost for all crib designs and is determined from equation 32. If the labor costs for crib construction are proportional to the material costs, the material costs can be used as the construction cost to compute the equivalent cost spacing. Employment at spacings greater than the equivalent cost spacing will provide a savings in the cost of employment. The equivalent cost spacing is useful in comparing the advantages of multi-timbered configurations with 2x2 crib designs.

EQ (COST) SPACE =

$$\frac{\text{CONS COST} - (\text{TL} \times \text{EMPLOY COST})}{\text{EMPLOY COST}}, \quad (32)$$

where EQ (COST) SPACE = equivalent cost spacing, ft,

CONS COST = construction cost for single crib, \$,

TL = length of timbers, ft,

and EMPLOY COST = employment cost per foot of entry, \$/ft.

The equivalent force spacing in which the cumulative force of the crib support systems are equal can be computed using equation 33.

$$\text{EQ (FORCE) SPACE} = \frac{F_{\text{Crib}} - (\text{TL} \times F_{\text{Supsys}})}{F_{\text{Supsys}}}, \quad (33)$$

where EQ (FORCE) SPACE = equivalent force spacing, ft,

F_{Crib} = individual crib resistance, kips,

F_{Supsys} = crib resistance per foot of mine entry, kips/ft,

and TL = timber length, ft.

DESIGN AND EMPLOYMENT PROCEDURE

The flow chart in figure 27 is the recommended procedure for the analysis of crib design and employment. Appendix B provides an example utilizing this procedure to optimize wood-crib design and employment for a long-wall tail-gate entry.

1. Determine the force and displacement design criteria for the crib support system.

a. Determine the critical load (F_{Critical}) and deflection (δ_{Critical}) required to produce failure of the immediate roof beam.

b. Estimate the failure height of the roof strata (h) and determine the weight of the associated detached rock mass (F_{Roof}). Specify the allowable entry closure (δ_{Allow})

that cannot be exceeded if ventilation and entry accessibility are to be maintained.

2. Determine the required crib stiffness and maximum capacity.

a. The required crib stiffness is determined from equation 17 by computing the crib capacity per foot of mine entry (F_{Supsys}) necessary to prevent roof failure.

b. The maximum required crib capacity per foot of mine entry equals the weight of detached rock mass per foot of mine entry (F_{Roof}).

c. Use the wood crib performance model to determine the crib capacity at displacements equal to the allowable entry closure ($F_{\text{Crib}} (\delta_{\text{Allow}})$) and the critical roof deflection ($F_{\text{Crib}} (\delta_{\text{Critical}})$) for the crib designs being considered. These capacities will be used to determine the crib spacing requirements in step 4.

3. Evaluate the interaction of the crib with the strata by assessing crib stability and roof-and-floor contact pressures.

a. Determine the range of displacement (δ_{Total}) through which the crib must provide support while maintaining stability. The design requirements developed by this model are valid only through 20-pct crib strain.

b. Determine the contact pressure (F_{psi}) developed at the mine roof and floor and compare with the strength of the roof-and-floor strata.

4. Define the crib support system by determining the spacing between cribs.

a. Determine the spacing (SPACE (δ_c)) based on the stiffness of the crib in relation to the strata loading required to produce deflection of the immediate roof beam to failure.

b. Establish the limits of crib spacing based on the crib capacity at the allowable entry closure in relation to the weight of a detached rock mass in the immediate roof (SPACE (δ_{Allow})), and the capability of the roof to span unsupported between cribs or other supports (SPACE (Span)).

c. The acceptable spacing is the minimum of SPACE (δ_c), SPACE (δ_{Allow}), and SPACE (Span).

5. Conduct a cost benefit analysis of the various crib support systems by comparing the costs of employment.

a. Determine the construction cost (CONS COST) per crib and the employment cost (EMPLOY COST) per lineal foot of supported roof for the designated crib spacing.

b. Evaluate equivalent cost (EQ (COST) SPACE) and equivalent force (EQ (FORCE) SPACE) spacing for the various crib designs.

6. Select a crib design and spacing that maximizes support resistance and minimizes support cost.

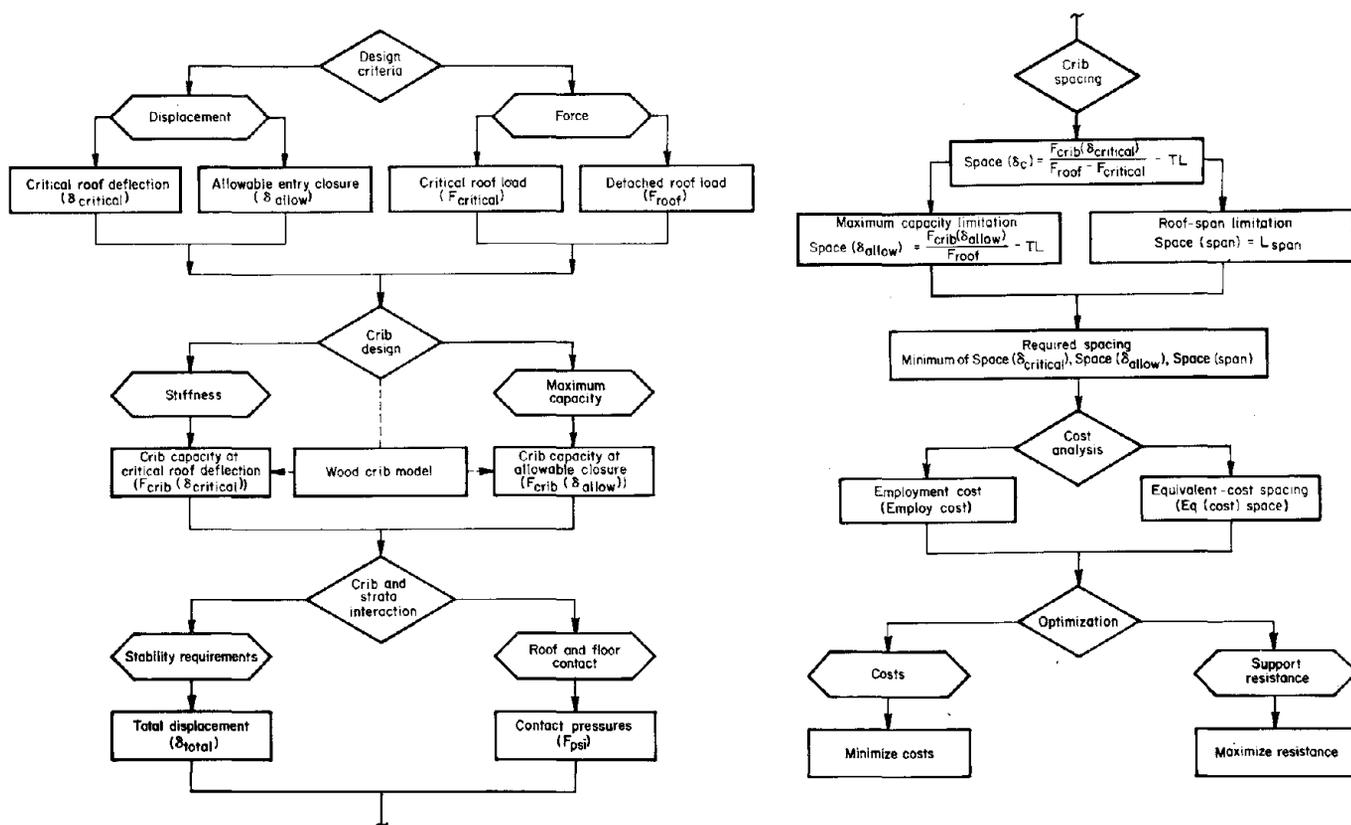


Figure 27.—Recommended procedure for analysis of crib design and employment.

CONCLUSIONS

The design and employment of wood cribs can be optimized if the load carrying characteristics of the crib and the load conditions imposed by the mine environment are understood. The models described in this report accurately predict the load-displacement relationship of wood cribs and facilitate a comparison of different crib designs and material constructions. The load conditions imposed by the mine environment are more difficult to model and there is no substitute for actual underground experience. Analytical models of roof behavior are provided to assist in defining load conditions for crib design.

It is imperative that the importance of the stiffness of the support structure be understood in designing ground-control systems for underground coal mining, particularly when designing passive support systems such as wood cribs. Too much attention frequently is given to the capacity of the support without recognition of the stiffness of the support structure. It is the development of the support capacity that is crucial to ground control. Wood cribs should develop sufficient capacity within a displacement that will prevent roof failure and provide safe and effective ground control. Hence, efforts to maximize

stiffness in relation to the volume of wood utilized in the construction of the crib should be a design priority.

An assessment of crib design and employment is based on five factors: (1) sufficient crib stiffness to provide adequate support to prevent deflection of the immediate roof to failure; (2) crib capacity required to support the weight of strata that become detached from stable roof structures within a displacement that will not compromise entry accessibility or ventilation; (3) stability through a displacement that includes the immediate roof deflection, pillar deformation, and floor heave; (4) assessment of the contact pressure acting on the mine roof and floor; and (5) determination of crib spacing based on the stiffness requirements to prevent roof failure, and limited by the crib capacity at the allowable entry closure, or the capability of the roof to span without support. The optimum crib design and employment is that providing the required capacity to stabilize the roof at minimal cost.

This methodology is most effective when the primary function of the wood crib is to provide support-system resistance to roof movements to maintain the integrity of the immediate roof structure. When the roof is highly

laminated and broken by the in situ stress fields, the amount of roof coverage provided by the secondary support system often is more critical than the capacity of the support. In these conditions, the beam theory will not adequately predict roof behavior. The design and employment requirements for the wood-crib support system should be based on the required roof coverage necessary to maintain roof stability. Additional support, such as wire meshing and truss bolting systems, often is needed to control the broken rock mass.

Conclusions regarding the engineering design and employment of wood-crib support systems using the models developed in this report are summarized as follows:

(1) Most wood crib systems in longwall gate roads employ one or two rows of 2×2 wood-crib constructions placed 5 to 8 ft apart. The examples discussed in the report demonstrate that 3×3 and 4×4 wood-crib designs are more cost effective than 2×2 designs, provided they can be spaced at distances commensurate with their higher capacity.

(2) The stiffness of wood cribs can be increased by increasing the number of timbers per layer or by increasing the width of the timber. The increased stiffness will provide greater resistance at less displacement, which will improve ground control when it is necessary to minimize roof sag. If the timber costs are directly proportional to the volume of wood, the use of wider timbers generally will provide lower employment costs than using more timbers per layer. Examples of crib designs that provide equal support include: (1) 2×2 with 6- by 6- by 36-in red oak timbers and a 3×3 with 4- by 4- by 36-in red oak timbers; (2) 2×2 with 8- by 8- by 36-in red oak timbers and 4×4 with 4- by 4- by 36-in red oak timbers; and (3) 3×3 with 8- by 8- by 36-in red oak timbers and a 4×4 with 6- by 6- by 36-in red oak timbers. The type of wood used in the crib construction is another design parameter that can be varied to provide the required crib stiffness.

(3) Using a conventional spacing of 5 ft with a 2×2 crib design, the equivalent cost spacing of 3×3 and 4×4 designs is 8.7 ft and 12.5 ft, respectively, for an 80-in-thick coal seam. Employment of multitimbered configurations at greater distances than the equivalent cost spacing will provide a savings in crib employment costs.

(4) A single row of 3×3 cribs will provide more capacity at less cost than a double row of 2×2 cribs. Therefore, a single row of cribs should be used in all cases where the roof is sufficiently stable to span between the crib and other support. Where the roof stability is threatened, consideration should be given to a rectangular 3×3 design where the long dimension is employed across the entry. The rectangular design will provide additional roof coverage where there is a preferred rock orientation while preserving the capacity enhancements of the 3×3 design.

(5) The response of wood cribs is height dependent. The stiffness of these support structures increase as the height decreases. Therefore, if the mining height changes significantly, the crib spacing should be adjusted accordingly. The increase in stiffness at lower mining heights will permit an increase in crib spacing, and the improved stability will permit the use of shorter timbers. However, the crib spacing must be consistent with the capability of the roof to span without support between the cribs. These measures will help to minimize support costs.

Proper construction methods are necessary to ensure optimum performance from crib support systems. Here are some recommendations to maximize crib efficiency:

(1) Wood cribs should be constructed with overhanging timbers. The minimum recommended overhang distance is one-half the width of the timber. Overhanging timber construction greatly enhances crib stability and provides a 10- to 15-pct increase in crib capacity.

(2) Wood cribs should be constructed from wood of the same species or similar compressive strength and hardness to avoid localized failures of individual timbers.

(3) While aspect ratios (height-to-width ratio) less than 5.0 provide acceptable crib performance, aspect ratios should be between 2.5 and 4.3 to provide efficient use of the wood timbers and to ensure stability through 20-pct strain. Timber should increase in length as the mining height increases to maintain an aspect ratio in this range. Recommended timber lengths as a function of mining height are shown in table 2, assuming a 6-in-wide timber and a 3-in overhang. A minimum timber length of 30 in is imposed by the Code of Federal Regulations.

Table 2.—Recommended timber lengths as a function of mining height

| <i>Mining height, ft</i> | <i>Timber length, in</i> |
|--------------------------|--------------------------|
| 4 | 30-31 |
| 6 | 30-41 |
| 8 | 34-50 |
| 10 | 40-60 |
| 12 | 45-70 |

(4) In multitimbered wood-crib constructions, maximum efficiency will be obtained if the distance between individual timbers in any one layer is greater than the width of the timber. The unstressed area between the timbers enhances the strength and stiffness of the crib.

(5) Wood cribs should be constructed to maximize the interlayer contact area. Hence, the wide side of the timber should be placed horizontally in the crib construction so that the aspect ratio of individual timbers remain less than or equal to 1. This construction will

provide maximum stability and support capacity. Also, construction of cribs that maximize interlayer contact area generally will provide the least employment cost, if the cribs can be spaced at distances commensurate with their capacity.

The extensive use of support systems constructed from wood timbers is likely to continue in underground coal mining. The engineering methods for the design and employment of wood cribs provided in this report will enhance the efficient utilization of these support systems. Future research regarding the design and employment of

wood cribs will focus on developing a better understanding of support and strata interaction so that improved design criteria can be developed. Current research efforts are to develop an improved rock mass classification system that better describes the stability of the strata in reference to pillar and artificial support design.

As a final comment, it must be understood that wood cribs are considered as secondary supports and are only part of the overall ground-control system. Entry stability also is affected by the performance of the coal pillars and roof bolts. Proper design of these primary supports is necessary to optimize wood-crib design and employment.

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APPENDIX A.—EXAMPLE WOOD-CRIB PERFORMANCE MODEL UTILIZATION

The example will calculate the load-displacement relationship for an 80-in-high, 3×3 crib constructed from red oak timbers with overhanging ends. The timber size is 5 by 6 by 30 in. The compressive strength perpendicular to the grain and the hardness for the red oak are identified in table 1 to be 987 psi and 1,145 lb, respectively.

1. The interlayer contact area is determined from equation 3.

$$\text{AREA}_{\text{Layer}} = (6 \times 6) \text{ in}^2 \times (3 \times 3) \text{ contacts} = 324 \text{ in}^2. \quad (\text{A-1})$$

2. The compressive strength coefficient is computed using equation 4.

$$A = 987 \text{ lb/in}^2 \times 324 \text{ in}^2 \times 10^{-3} = 319.8 \text{ kips}. \quad (\text{A-2})$$

3. The crib is constructed with overhanging ends, so equation 5a is used to convert the wood hardness value to the plastic modulus for the mine timber.

$$E_p = 4.633 \times 1,145 \text{ lb} - 1,060 = 4,245 \text{ psi}. \quad (\text{A-3})$$

4. The plastic timber stiffness for one contact area is computed from equation 6.

$$\begin{aligned} K_t &= \frac{4,245 \text{ lb/in}^2 \times (6 \times 6) \text{ in}^2}{5 \text{ in}} \times 10^{-3} \\ &= 30.6 \text{ kips/in}. \end{aligned} \quad (\text{A-4})$$

5. The plastic stiffness coefficient (K_p) is computed using equation 7.

$$K_p = \frac{30.6 \text{ kips/in} \times 9 \text{ contacts}}{16 \text{ layers}} = 17.2 \text{ kips/in}. \quad (\text{A-5})$$

6. Determine the adjustment factors for height, percentage of timber contact area, aspect ratio, and construction without overhanging timbers.

The height factor (HTFCT) is computed as 0.68 using equation 8.

$$\text{HTFCT} = 1.62 - 0.0117 \times 80 \text{ in} = 0.68. \quad (\text{A-6})$$

The percentage of timber contact area (PCTFCT) is computed from equation 10b as 60 pct for the 3×3 configuration using 5- by 6- by 30-in timbers. Since this is greater than 55 pct, PCTFCT equals 0.9.

$$\text{AREA}_{\text{Pct}} = \frac{6 \times 3}{30} \times 100 = 60 \text{ pct}. \quad (\text{A-7})$$

$$\text{PCTFCT} = 0.9. \quad (\text{A-8})$$

The aspect ratio (AR) for the 80-in-high crib constructed from 30-in-long timbers with 3 in of overhang on each end is computed as 4.44, which makes the aspect ratio factor (ARFCT) equal to 0.94.

$$\text{AR} = \frac{80}{30 - (2 \times 3) - 6} = 4.44. \quad (\text{A-9})$$

$$\text{ARFCT} = 2.41 - (0.33 \times 4.44) = 0.94. \quad (\text{A-10})$$

Since the crib is constructed with overhanging timbers, the overhanging timbers factor (OHFCT) equals 1.

Therefore, the following equation represents the force-displacement relationship for this crib. Figure 18 compares the model prediction to a full-scale test of a 3×3 crib in the mine roof simulator.

$$\begin{aligned} F_{\text{Crib}} (3 \times 3) &= 319.8 \times 1 \times 0.9 \times \left(1 - e^{-(0.68) \times \delta} \right) \\ &+ 0.9 \times 0.94 \times 17.2 \times \delta \text{ kips}. \end{aligned} \quad (\text{A-11})$$

$$\begin{aligned} F_{\text{Crib}} (3 \times 3) &= 287.8 \times \left(1 - e^{(0.68) \times \delta} \right) \\ &+ 14.6 \times \delta \text{ kips}. \end{aligned} \quad (\text{A-12})$$

APPENDIX B.—WOOD-CRIB DESIGN AND EMPLOYMENT EXAMPLE

This example considers the support of a 20-ft longwall tailgate entry with a bedded roof structure. The immediate roof bed is 15 in thick with a tensile strength of 1,500 psi, a modulus of elasticity of 2×10^6 psi, and a density of 155 lb/ft³. The 80-in-thick seam is located 750 ft below the surface. The coal has a modulus of elasticity of 350,000 psi. The cribs are to be constructed from 5- by 6- by 30-in red oak timbers with overhanging timbers (3 in of overhang on each timber). The unit cost per timber is \$1.37, based on \$220/1,000 board ft.

FORCE AND DISPLACEMENT DESIGN CRITERIA

The critical deflection is determined from equation 16b, assuming a pinned-end beam condition. This is the deflection required to produce failure of the immediate roof beam. The width of the yield zone in the pillars adjacent to the entry at a depth of cover of 750 ft is determined from figure 23 to be 10 ft, providing a beam length of 40 ft in accordance with equation 15. The critical deflection is computed as 2.4 in for these conditions.

$$\delta_{\text{Critical}} = \frac{5 \times 1,500 \times (40 \times 12)^2}{24 \times (2.0 \times 10^6) \times 15} = 2.4 \text{ in.} \quad (\text{B-1})$$

The load required to produce deflection of the immediate roof beam to failure is computed as 11.3 kips/ft of entry from equation 17b.

$$F_{\text{Critical}} = \frac{4 \times 1,500 \times 15^2}{3 \times 40 \times 12} \times 12 \times 10^{-3} = 11.3 \frac{\text{kips}}{\text{ft}}. \quad (\text{B-2})$$

A caving height of approximately 12 ft is determined from equation 19 based on an RMR rating of 40. This failure height provides a strata load of 29.2 kips/ft (equation 21). The strata load is computed from the weight of rock below the pressure arch.

$$h = \frac{(100 - 40)}{100} \times 20 = 12 \text{ ft.} \quad (\text{B-3})$$

$$F_{\text{Roof}} = \frac{1}{2} \times 3.1416 \times \frac{20}{2} \times 12 \times 155 \times 10^{-3} \\ = 29.2 \text{ kips/ft.} \quad (\text{B-4})$$

The allowable entry closure is 12 in. This criterion is imposed from past mine experience and is considered essential for safe passage through the entry.

CRIB STIFFNESS AND MAXIMUM CAPACITY

The stiffness of the crib support system is determined from equation 18 with a critical beam load of 11.3 kips/ft and an imposed strata load of 29.2 kips/ft. It is required that the crib support system provide 17.9 kips/ft of resistance at 2.4 in of displacement (δ_{Critical}). The maximum required crib-support system capacity equals 29.2 kips/ft in accordance with equation 22.

$$F_{\text{Supsys}} = 29.2 - 11.3 = 17.9 \text{ kips/ft.} \quad (\text{B-5})$$

$$F_{\text{Supsys}} (\text{Max}) = 29.2 - 0 = 29.2 \text{ kips/ft.} \quad (\text{B-6})$$

The next step is to determine the performance characteristics of wood-crib designs being considered for employment. From table 1, a hardness value of 1,145 lb and a compressive strength of 987 psi for the red oak timbers are identified. Since the crib is constructed from 5- by 6-in-cross-section timbers, 16 layers are required to provide an 80-in-high structure. These factors are used to compute coefficients that are used to determine the crib stiffness and capacity using equations 3 through 14. Computations for 2×2, 3×3, and 4×4 configurations are shown below.

The interlayer contact area values are

$$\text{AREA}_{\text{Layer}} (2 \times 2) = (6 \times 6) \times (2 \times 2) = 144 \text{ in}^2, \quad (\text{B-7a})$$

$$\text{AREA}_{\text{Layer}} (3 \times 3) = (6 \times 6) \times (3 \times 3) = 324 \text{ in}^2, \quad (\text{B-7b})$$

$$\text{and } \text{AREA}_{\text{Layer}} (4 \times 4) = (6 \times 6) \times (4 \times 4) \\ = 576 \text{ in}^2. \quad (\text{B-7c})$$

The compressive strength coefficient (A) values are

$$A(2 \times 2) = 987 \times 144 \times 10^{-3} = 142.1 \text{ kips,} \quad (\text{B-8a})$$

$$A(3 \times 3) = 987 \times 324 \times 10^{-3} = 319.8 \text{ kips,} \quad (\text{B-8b})$$

$$\text{and } A(4 \times 4) = 987 \times 576 \times 10^{-3} = 568.5 \text{ kips.} \quad (\text{B-8c})$$

The plastic stiffness coefficient (E_p) is

$$E_p = 4.633 \times 1,145 - 1,060 = 4,245 \text{ psi. (B-9)}$$

The timber stiffness (K_t) is

$$K_t = \frac{4,245 \times (6 \times 6)}{5} \times 10^{-3} = 30.6 \frac{\text{kips}}{\text{in}}. \quad (\text{B-10})$$

The plastic crib stiffness (K_p) values are

$$K_p(2 \times 2) = \frac{30.6 \times 4}{16} = 7.7 \frac{\text{kips}}{\text{in}}, \quad (\text{B-11a})$$

$$K_p(3 \times 3) = \frac{30.6 \times 9}{16} = 17.2 \frac{\text{kips}}{\text{in}}, \quad (\text{B-11b})$$

and
$$K_p(4 \times 4) = \frac{30.6 \times 16}{16} = 30.6 \frac{\text{kips}}{\text{in}}. \quad (\text{B-11c})$$

The adjustment factors:

(1) Height factor (HTFCT),

$$\text{HTFCT} = 1.62 - (0.0117 \times 80) = 0.68. \quad (\text{B-12})$$

(2) Percentage of timber contact area (PCTFCT),

$$\text{AREA}_{\text{Pct}}(2 \times 2) = \frac{\frac{144}{4} \times 2}{6 \times 30} \times 100 = 40 \text{ pct}, \quad (\text{B-13a})$$

$$\text{AREA}_{\text{Pct}}(3 \times 3) = \frac{\frac{324}{9} \times 3}{6 \times 30} \times 100 = 60 \text{ pct}, \quad (\text{B-13b})$$

$$\text{AREA}_{\text{Pct}}(4 \times 4) = \frac{\frac{576}{16} \times 4}{6 \times 30} \times 100 = 80 \text{ pct}, \quad (\text{B-13c})$$

$$\text{PCTFCT}(2 \times 2) = 1.0, \quad (\text{B-14a})$$

$$\text{PCTFCT}(3 \times 3) = 0.9, \quad (\text{B-14b})$$

$$\text{and } \text{PCTFCT}(4 \times 4) = 0.9. \quad (\text{B-14c})$$

(3) Aspect ratio factor (ARFCT). Since all crib configurations are of the same height and constructed from 5- by 6- by 30-in timbers with 3 in of overhang on each end, the Aspect Ratio (AR) as computed by equation 10 is the same for all the three configurations, making the Aspect Ratio Factor (ARFCT) equal to 0.94 for the three crib designs.

$$\text{AR} = \frac{80}{30 - (2 \times 3) - 6} = 4.44, \quad (\text{B-15})$$

and

$$\begin{aligned} \text{ARFCT}(2 \times 2, 3 \times 3, 4 \times 4) &= 2.41 - (0.33 \times 4.44) \\ &= 0.94. \end{aligned} \quad (\text{B-16})$$

(4) Overhanging timber construction factor (OHFCT). All cribs are constructed with overhanging timbers; hence, the overhanging timber factor equals 1.0 for all three crib designs.

The characteristic equations for computing the capacity of 2x2, 3x3, and 4x4 wood-crib designs at the critical beam deflection are as follows:

$$\begin{aligned} F_{\text{Crib}}(2 \times 2) &= 142.1 \times 1.0 \times 1.0 \times \left(1 - e^{-(0.68) \times (2.4)}\right) \\ &\quad + 1.0 \times 0.94 \times 7.7 \times 2.4 = 131.6 \text{ kips}, \end{aligned} \quad (\text{B-17a})$$

$$\begin{aligned} F_{\text{Crib}}(3 \times 3) &= 319.1 \times 1.0 \times 0.9 \times \left(1 - e^{-(0.68) \times (2.4)}\right) \\ &\quad + 0.9 \times 0.94 \times 17.2 \times 2.4 = 266.0 \text{ kips}, \end{aligned} \quad (\text{B-17b})$$

and

$$\begin{aligned} F_{\text{Crib}}(4 \times 4) &= 568.5 \times 1.0 \times 0.9 \times \left(1 - e^{-(0.68) \times (2.4)}\right) \\ &\quad + 0.9 \times 0.94 \times 30.6 \times 2.4 \\ &= 473.7 \text{ kips}. \end{aligned} \quad (\text{B-17c})$$

The characteristic equations for the 2×2, 3×3, and 4×4 configurations at the allowable entry closure are as follows:

$$F_{\text{Crib}} (2 \times 2) = 142.1 \times 1.0 \times 1.0 \left(1 - e^{-(0.68) \times (12)} \right) \\ + 1.0 \times 0.94 \times 7.7 \times 12 = 228.9 \text{ kips, (B-18a)}$$

$$F_{\text{Crib}} (3 \times 3) = 319.1 \times 1.0 \times 0.9 \times \left(1 - e^{-(0.68) \times (12)} \right) \\ + 0.9 \times 0.94 \times 17.2 \times 12 = 461.6 \text{ kips, (B-18b)}$$

and

$$F_{\text{Crib}} (4 \times 4) = 568.5 \times 1.0 \times 0.9 \times \left(1 - e^{-(0.68) \times (12)} \right) \\ + 0.9 \times 0.94 \times 30.6 \times 12 = 821.7 \text{ kips. (B-18c)}$$

CRIB AND STRATA INTERACTION

The total displacement through which the crib must provide resistance and maintain stability is the sum of the roof deflection, pillar deformation, and floor heave as described in equation 23. Roof deflection was previously computed as 2.4 in. Pillar deformation is computed as 0.9 in from equation 24. If no floor heave is expected, then the maximum convergence through which the crib must provide resistance is 3.3 in.

$$\delta_{\text{Pillar}} = 1.1 \times 750 \times 5 \times \frac{80}{350,000} = 0.9 \text{ in. (B-19)}$$

$$\delta_{\text{Total}} = 2.4 + 0.9 + 0 = 3.3 \text{ in. (B-20)}$$

The contact pressure for the crib designs is computed from equation 25. Contact area for the 3×3 and 4×4 configuration equals the full timber area.

$$F_{\text{Psi}} (2 \times 2) = \frac{228.9}{2 \times (6)^2 \times 4} \times 10^3 = 794.8 \text{ psi, (B-21a)}$$

$$F_{\text{Psi}} (3 \times 3) = \frac{461.6}{6 \times 30 \times 3} \times 10^3 = 854.8 \text{ psi, (B-21b)}$$

and

$$F_{\text{Psi}} (4 \times 4) = \frac{821.7}{6 \times 30 \times 4} \times 10^3 = 1,141.3 \text{ psi. (B-21c)}$$

The bearing capacity of the roof is 3,500 psi and the bearing capacity of the floor is 2,000 psi, as determined from in-mine tests. Therefore, none of the crib pressures will exceed the roof or floor strength.

SUMMARY OF DESIGN REQUIREMENTS

A summary of design requirements is shown in table B-1.

Table B-1.—Design requirements for example 1

| Design criteria | Requirements |
|---------------------------------------------------------------------------------------------------|--------------|
| Critical deflection (δ_{Critical}) in . . | 2.4 |
| Allowable entry closure (δ_{Allow}) in . . | 12.0 |
| Critical load (F_{Critical}) kip/ft . . | 11.3 |
| Strata load (F_{Roof}) kip/ft . . | 29.2 |
| Stiffness requirements (F_{Supsys} at δ_{Critical}) kip/ft . . | 17.9 |
| Stability requirement (δ_{Total}) in . . | 3.3 |
| Floor bearing strength psi . . | 2,000 |
| Roof bearing strength psi . . | 3,500 |

CRIB SPACING

The crib spacing based on stiffness requirements for the 2×2, 3×3, and 4×4 configurations is determined from equation 26.

$$\text{SPACE } (\delta_C) (2 \times 2) = \frac{131.6}{29.2 - 11.3} - 2.5 \\ = 4.9 \text{ ft, (B-22a)}$$

$$\text{SPACE } (\delta_C) (3 \times 3) = \frac{266.0}{29.2 - 11.3} - 2.5 \\ = 12.4 \text{ ft, (B-22b)}$$

$$\text{and SPACE } (\delta_C) (4 \times 4) = \frac{473.7}{29.2 - 11.3} - 2.5 \\ = 24.0 \text{ ft. (B-22c)}$$

No limitation on spacing is imposed by the crib capacity at the allowable entry closure and the detached roof load. The 4×4 configuration is limited by the maximum unsupported roof span of 13.3 ft.

$$\text{SPACE } (\delta_{\text{Allow}}) (2 \times 2) = \frac{228.9}{29.2} - 2.5 \\ = 5.3 \text{ ft, (B-23a)}$$

$$\begin{aligned} \text{SPACE } (\delta_{\text{Allow}}) (3 \times 3) &= \frac{461.6}{29.2} - 2.5 \\ &= 13.3 \text{ ft,} \end{aligned} \quad (\text{B-23b})$$

$$\begin{aligned} \text{SPACE } (\delta_{\text{Allow}}) (4 \times 4) &= \frac{821.7}{29.2} - 2.5 \\ &= 25.6 \text{ ft,} \end{aligned} \quad (\text{B-23c})$$

and

$$\begin{aligned} \text{SPACE (Span)} = L_{\text{Span}} &= \frac{4 \times (15^2 \times (1,500/3))}{3 \times 11.3 \times 10^3} \\ &= 13.3 \text{ ft.} \end{aligned} \quad (\text{B-24})$$

Therefore, the designated spacing for the 2×2, 3×3, and 4×4 crib designs are 4.9 ft, 12.4 ft, and 13.3 ft, respectively. At these crib spacings, the maximum required capacity per crib can be computed using equation 31.

$$\begin{aligned} F_{\text{Crib}} (\text{Max}) (2 \times 2) &= 29.2 \times (4.9 + 2.5) \\ &= 216.0 \text{ kips,} \end{aligned} \quad (\text{B-25a})$$

$$\begin{aligned} F_{\text{Crib}} (\text{Max}) (3 \times 3) &= 29.2 \times (12.4 + 2.5) \\ &= 435.1 \text{ kips,} \end{aligned} \quad (\text{B-25b})$$

$$\begin{aligned} \text{and } F_{\text{Crib}} (\text{Max}) (4 \times 4) &= 29.2 \times (13.3 + 2.5) \\ &= 461.4 \text{ kips.} \end{aligned} \quad (\text{B-25c})$$

COST ANALYSIS

The price of a 5- by 6- by 30-in timber is \$1.37. Therefore, the material cost for construction of a 2×2, 3×3, and 4×4 crib in the 80-in seam height is \$44.00, \$66.00, and \$88.00, respectively. The employment cost per foot of supported roof at the designated crib spacing for these configurations is \$5.95, \$4.43, and \$5.57/ft of entry, respectively. It is assumed that the labor costs are in direct proportion to the material costs. Therefore, the labor costs are eliminated from the employment cost comparison.

$$\text{EMPLOY COST } (2 \times 2) = \frac{44}{4.9 + 2.5} = \frac{\$5.95}{\text{ft}}, \quad (\text{B-26a})$$

$$\text{EMPLOY COST } (3 \times 3) = \frac{66}{12.4 + 2.5} = \frac{\$4.43}{\text{ft}}, \quad (\text{B-26b})$$

and

$$\text{EMPLOY COST } (4 \times 4) = \frac{88}{13.3 + 2.5} = \frac{\$5.57}{\text{ft}}. \quad (\text{B-26c})$$

The equivalent cost spacing is determined from equation 28.

$$\begin{aligned} \text{EQ (COST) SPACE } (2 \times 2) &= \frac{44.00 - (2.5 \times 5.95)}{5.95} \\ &= 4.9 \text{ ft,} \end{aligned} \quad (\text{B-27a})$$

$$\begin{aligned} \text{EQ (COST) SPACE } (3 \times 3) &= \frac{66.00 - (2.5 \times 5.95)}{5.95} \\ &= 8.6 \text{ ft,} \end{aligned} \quad (\text{B-27b})$$

and

$$\begin{aligned} \text{EQ (COST) SPACE } (4 \times 4) &= 88.00 - \frac{(2.5 \times 5.95)}{5.95} \\ &= 12.3 \text{ ft.} \end{aligned} \quad (\text{B-27c})$$

Hence, for the load conditions assumed in this example, the 3×3 cribs must be placed at least 8.6 ft apart and the 4×4 cribs at least 12.3 ft apart to be employed at less cost than the 2×2 cribs on a 4.9-ft spacing. Spacings that provide equal support by the crib support system are determined from equation 34.

$$\begin{aligned} \text{EQ (FORCE) SPACE } (2 \times 2) &= \frac{132 - (2.5 \times 17.9)}{17.9} \\ &= 4.9 \text{ ft,} \end{aligned} \quad (\text{B-28a})$$

$$\begin{aligned} \text{EQ (FORCE) SPACE } (3 \times 3) &= \frac{266 - (2.5 \times 17.9)}{17.9} \\ &= 12.4 \text{ ft,} \end{aligned} \quad (\text{B-28b})$$

and

$$\begin{aligned} \text{EQ (FORCE) SPACE } (4 \times 4) &= \frac{473 - (2.5 \times 17.9)}{17.9} \\ &= 24.0 \text{ ft.} \end{aligned} \quad (\text{B-28c})$$

DESIGN AND EMPLOYMENT OPTIMIZATION

The 3×3 configuration employed on a 12.4-ft spacing provides the required support at minimal cost and is

chosen as the optimum crib design and employment. The employment of the 3×3 configuration on a 12.4-ft spacing would provide a savings in materials of \$1,520/1,000 ft of entry compared to a 2×2 configuration on a 4.9-ft spacing.

Table B-2.—Employment strategy for example 1

| Performance measure | 2×2 crib | 3×3 crib | 4×4 crib |
|-------------------------------------------------------------------------------------------|----------|----------|----------|
| Capacity at critical deflection (F_{Crib} (2.4)) kip .. | 132 | 266 | 474 |
| Capacity at allowable entry closure (F_{Crib} (12.0)) kip .. | 229 | 462 | 822 |
| Crib spacing based on stiffness requirements (SPACE (δ_j)) ft .. | 4.9 | 12.4 | 24.0 |
| Crib spacing based on detached roof load (SPACE (δ_{Allow})) ft .. | 5.3 | 13.3 | 25.6 |
| Unsupported roof span limitation (L_{Span}) ft .. | 13.3 | 13.3 | 13.3 |
| Designated crib spacing (SPACING) ft .. | 4.9 | 12.4 | 13.3 |
| Maximum required crib capacity at designated spacing kip .. | 216 | 435 | 461 |
| Roof-and-floor contact pressure at allowable entry closure (F_{psi}) psi .. | 795 | 855 | 1,141 |
| Employment material cost at designated spacing (EMPLOY COST) \$/ft .. | 5.95 | 4.43 | 5.57 |
| Equivalent cost spacing (EQ (COST) SPACE) ft .. | 4.9 | 8.6 | 12.3 |
| Equivalent force spacing (EQ (FORCE) SPACE) ft .. | 4.9 | 12.4 | 24.0 |

APPENDIX C.—COMPARING CURRENT SUPPORT SYSTEM WITH ALTERNATIVE CRIB DESIGNS

This example compares 3×3 and 4×4 crib designs to a mine's 2×2 crib system and determines the optimum placement of these alternative systems. The 2×2 design is constructed from 5- by 6- by 30-in red oak timbers, and is employed in single row arrangement on 5-ft spacing in an 80-in coal seam. Mine experience has shown that roof sag (deflection) must be controlled to less than 2.4 in to maintain roof stability.

The force displacement relationship for the 2×2 crib construction is computed from the wood-crib performance model. The resistive force provided by the crib at 2.4 in of displacement is 132 kips, which translates to 17.6 kips/ft of entry for a 5-ft crib spacing.

$$F_{\text{Crib}}(2 \times 2) = 142.1 \times \left(1 - e^{-(0.68) \times (\delta)}\right) + 7.2 \times \delta. \quad (\text{C-1a})$$

Choosing the timber length is the first priority for the 3×3 and 4×4 designs. The optimum timber length is that which is least expensive while maintaining an aspect ratio between 2.5 and 5.0 for the crib structure. On this basis, 30-in timber length is selected.

The model equations for the 3×3 and 4×4 configurations are shown below and compared with the 2×2 design in figure C-1. Using these equations to compute the crib resistance at 2.4 in of displacement, it is found from equation C-2a that the 3×3 crib design can be spaced 12.6 ft apart and provide the same resistance to roof loading as the current 2×2 design. Likewise, the 4×4 design could be spaced at 24.4 ft and provide equal resistance.

$$F_{\text{Crib}}(3 \times 3) = 287.8 \times \left(1 - e^{-(0.68) \times (\delta)}\right) + 14.6 \times \delta, \quad (\text{C-1b})$$

and

$$F_{\text{Crib}}(4 \times 4) = 511.7 \times \left(1 - e^{-(0.68) \times (\delta)}\right) + 25.9 \times \delta, \quad (\text{C-1c})$$

$$\begin{aligned} \text{EQ (FORCE) SPACE } (3 \times 3) &= \frac{266 - (2.5 \times 17.6)}{17.6} \\ &= 12.6 \text{ ft}, \quad (\text{C-2a}) \end{aligned}$$

$$\begin{aligned} \text{and EQ (FORCE) SPACE } (4 \times 4) &= \frac{474 - (2.5 \times 17.6)}{17.6} \\ &= 24.4 \text{ ft}. \quad (\text{C-2b}) \end{aligned}$$

Since 10 ft is considered the maximum acceptable unsupported roof span, the 3×3 design on 10-ft spacing is the optimum crib design and employment. This design will provide a cost savings of 10 pct with over 20 pct more support force than the current 2×2 support system.

$$\text{EMPLOY COST } (2 \times 2) = \frac{44}{5.0 + 2.5} = \frac{\$5.87}{\text{ft}}, \quad (\text{C-3a})$$

and

$$\text{EMPLOY COST } (3 \times 3) = \frac{66}{10.0 + 2.5} = \frac{\$5.28}{\text{ft}}. \quad (\text{C-3b})$$

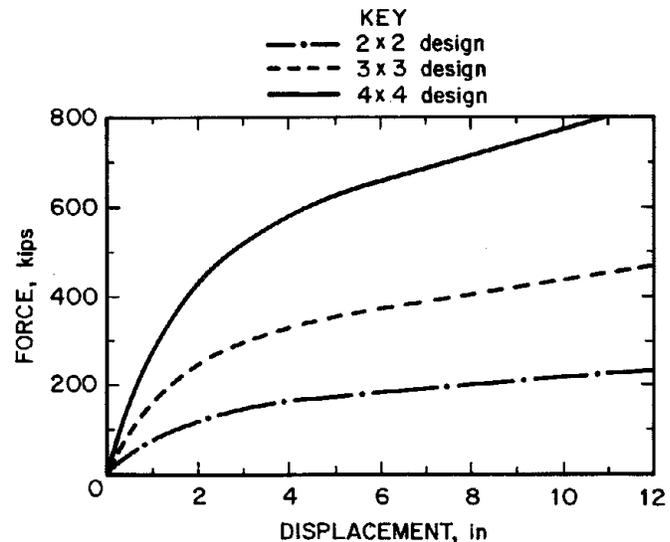


Figure C-1.—Comparison of 2×2, 3×3, and 4×4 wood-crib performance.

APPENDIX D.—LIST OF EQUATIONS

$$F_{\text{Crib}} = A \times \text{OHFCT} \times \text{PCTFCT} \times (1 - e^{-(\text{HTFCT}) \times (\delta)}) + \text{PCTFCT} \times \text{ARFCT} \times K_p \times \delta. \quad (1)$$

$$\text{CS}_{0.04} = 1.589 \times \text{CS}_{\text{PL}} + 42.44. \quad (2)$$

$$\text{AREA}_{\text{Layer}} = \text{AREA}_{\text{Contact}} \times \text{CONTACTS}. \quad (3)$$

$$A = \text{STRENGTH} \times \text{Area}_{\text{Layer}} \times 10^{-3}. \quad (4)$$

$$E_p = 4.63 \times \text{HARDNESS} - 1,060, \quad (5a)$$

(with overhang).

$$E_p = 4.45 \times \text{HARDNESS} = 1,400, \quad (5b)$$

(without overhang).

$$K_t = \frac{E_p \times \text{AREA}}{\text{THICKNESS}} \times 10^{-3}. \quad (6)$$

$$K_p = \frac{K_t \times \text{CONTACTS}}{\text{LAYERS}}. \quad (7)$$

$$\text{HTFCT} = 1.62 - 0.0117 \times \text{Crib Height}. \quad (8)$$

$$\text{PCTFCT} = 0.9 \text{ when } \text{AREA}_{\text{Pct}} \geq 55 \text{ Pct}. \quad (9a)$$

$$\text{PCTFCT} = 1.0 \text{ when } \text{AREA}_{\text{Pct}} < 55 \text{ Pct}. \quad (9b)$$

$$\text{AREA}_{\text{Pct}} = \frac{\frac{\text{AREA}_{\text{Layer}}}{\text{CONTACTS}} \times \text{TIMBERS}}{\text{TW} \times \text{TL}} \times 100. \quad (10a)$$

$$\text{AREA}_{\text{Pct}} = \frac{\text{TW} \times \text{TIMBERS}}{\text{TL}} \times 100. \quad (10b)$$

$$\text{ARFCT} = 2.41 - (0.33 \times \text{AR}) \text{ when } \text{AR} \geq 4.3. \quad (11a)$$

$$\text{ARFCT} = 1.0 \text{ when } \text{AR} < 4.3. \quad (11b)$$

$$\text{AR} = \frac{\text{HEIGHT}}{\text{TL} - (2 \times \text{OVERHANG}) - \text{TW}}. \quad (12)$$

$$\text{OHFCT} = 0.9 \text{ when cribs are constructed without overhanging timbers}. \quad (13a)$$

$$\text{OHFCT} = 1.0 \text{ when cribs are constructed with overhanging timbers}. \quad (13b)$$

$$L = W + Y_{P1} + Y_{P2}. \quad (14)$$

$$\delta_{\text{Critical}} = \frac{\sigma \times L^2}{16 \times E \times t}, \text{ fixed-end}. \quad (15a)$$

$$\delta_{\text{Critical}} = \frac{5 \times \sigma \times L^2}{24 \times E \times t}, \text{ pinned-end}. \quad (15b)$$

$$F_{\text{Critical}} = \frac{2 \times t^2 \times \sigma}{L} \times 12 \times 10^{-3}, \text{ fixed-end}. \quad (16a)$$

$$F_{\text{Critical}} = \frac{4 \times t^2 \times \sigma}{3 \times L} \times 12 \times 10^{-3}, \text{ pinned-end}. \quad (16b)$$

$$F_{\text{Roof}} - F_{\text{Supsys}} < F_{\text{Critical}}. \quad (17)$$

$$h = \frac{(100 - \text{RMR})}{100} \times w. \quad (18)$$

$$F_{\text{Roof}} = w \times h \times \gamma \times 10^{-3}. \quad (19)$$

$$F_{\text{Roof}} = \frac{1}{2} \times \pi \times \frac{w}{2} \times h \times \gamma \times 10^{-3}. \quad (20)$$

$$F_{\text{Supsys}} (\text{Max}) = F_{\text{Roof}}. \quad (21)$$

$$\delta_{\text{Total}} = \delta_{\text{ROOF}} + \delta_{\text{PILLAR}} + \delta_{\text{FLOOR}}. \quad (22)$$

$$\delta_{\text{Pillar}} = \sigma_V \times A \times \frac{L}{E}. \quad (23)$$

$$F_{\text{Psi}} = \frac{F_{\text{Crib}}}{2 \times (\text{TW})^2 \times \text{CONTACTS}} \times 10^3. \quad (24)$$

$$\text{SPACE } (\delta_c) = \frac{F_{\text{Crib}} (\delta_{\text{Critical}})}{F_{\text{Roof}} - F_{\text{Critical}}} - \text{TL}. \quad (25)$$

$$\text{SPACE } (\delta_{\text{Allow}}) = \frac{F_{\text{Crib}} (\delta_{\text{Allow}})}{F_{\text{Roof}}} - \text{TL}. \quad (26)$$

$$\text{SPACE (SPAN)} = L_{\text{Span}}. \quad (27)$$

$$L_{\text{Span}} = \frac{2 \times t^2 \times (\sigma/SF)}{F_{\text{Critical}}}, \text{ fixed-end.} \quad (28a)$$

$$L_{\text{Span}} = \frac{4 \times t^2 \times (\delta/SF)}{3 \times F_{\text{Critical}}}, \text{ pinned-end.} \quad (28b)$$

$$\text{SPACING} = \text{Minimum of SPACE } (\delta_c),$$

$$\text{SPACE } (\delta_{\text{Allow}}),$$

$$\text{SPACE (SPAN)}. \quad (29)$$

$$F_{\text{Crib}} (\text{Max}) = F_{\text{Roof}} \times (\text{SPACING} + \text{TL}). \quad (30)$$

$$\text{EMPLOY COST} = \frac{\text{CONS COST}}{\text{SPACING} + \text{TL}}. \quad (31)$$

$$\text{EQ (COST) SPACE} =$$

$$\frac{\text{CONS COST} - (\text{TL} \times \text{EMPLOY COST})}{\text{EMPLOY COST}}. \quad (32)$$

$$\text{EQ (FORCE) SPACE} =$$

$$\frac{F_{\text{Crib}} - (\text{TL} \times F_{\text{Supsys}})}{F_{\text{Supsys}}}. \quad (33)$$