

# ENGINEERING METHOD FOR THE DESIGN AND PLACEMENT OF WOOD CRIBS

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## ABSTRACT

Wood cribs are used extensively to stabilize mine openings by providing resistance to deflections of the immediate mine roof and floor and by supporting the weight of unstable rock masses. While the unit costs of these supports are relatively low, their extensive use results in significant costs to coal mine operators. The U.S. Bureau of Mines (USBM) has developed a Wood Crib Performance Model that computes the load capacity of wood cribs as a function of the displacement of the crib structure induced

by mine roof and floor convergence. This permits comparison of the loading characteristics of various crib constructions and enables systems to be designed with consideration of the load conditions imposed by the mine environment. The design method matches the stiffness, strength, and stability of the crib structure with expected rock mass behavior to determine a crib design and employment spacing that will provide the lowest cost support.

## INTRODUCTION

Combinations of roof bolts, cribs, posts, and beams are often used to stabilize mine openings to provide a safer underground environment for mineworkers. Roof bolts and cribs are used most often. Crib supports are simple in design, with a material cost of less than \$70 per meter of height, but their extensive use results in significant costs to coal mine operators. One mine operator estimates that \$1 million is spent annually in crib construction for support of its longwall gate roads.<sup>3</sup>

As part of the USBM's program to reduce underground hazards to mineworkers through the development of improved ground control technologies, researchers conducted full-scale tests of crib support systems in the 13,350-kN (3-million-lb) mine roof simulator at the USBM's Pittsburgh Research Center (figure 1). The results obtained permit a comparison of wood crib performance and have led to the development of a Wood Crib Performance Model that predicts the force-displacement behavior of wood cribs. The model can accurately predict the performance of cribs where the type of wood, timber dimensions, and construction configuration are varied. This model will assist the mine operator in selecting the optimum crib design and employment strategy to safely stabilize its mine openings at minimal cost.

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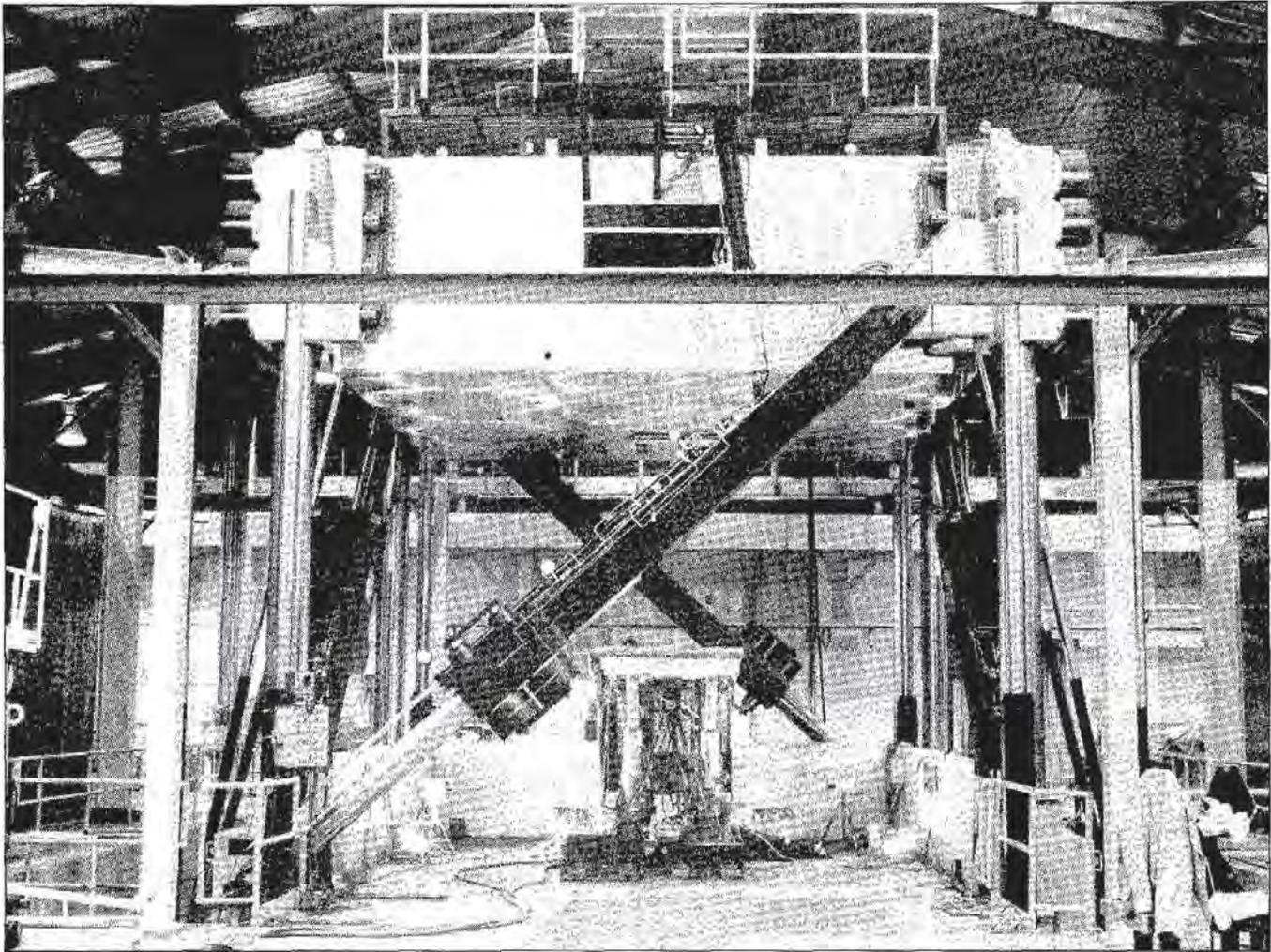


Figure 1.—Mine roof simulator at the USBM's Pittsburgh Research Center, where researchers conducted full-scale tests of crib support systems.

## SUPPORT CONSTRUCTION AND LOADING BEHAVIOR

Wood cribs are constructed from layers of two or more parallel timbers. Each successive layer is placed perpendicularly to the previous layer to form an open-box arrangement, as shown in figure 2. Subsequent layers are stacked until the entry height is reached. The configuration is described by the number of timbers per layer. Two-timber-per-layer construction (2×2) is used most often to minimize unit costs. Timber lengths typically range from 76.2 to 152.4 cm (30 to 60 in).

The force-displacement relationship for a wood crib follows a distinct pattern, as shown in figure 3 (1-2).<sup>4</sup> Two

regions of proportional behavior are followed by a region of nonlinear behavior. Initially, the crib is stiff and the resistive force increases quickly as a linear function of displacement. This phase describes elastic wood behavior and occurs during the initial 5-pct strain. The crib stiffness then decreases as the wood yields during linear plastic deformation. Plastic deformation occurs up to 25- or 30-pct strain. Beyond 25- or 30-pct strain, the crib exhibits nonlinear behavior that depends on the stability of the structure. The force will increase if the crib is stable, whereas the force will decrease if the structure is unstable.

<sup>4</sup>Italic numbers in parentheses refer to items in the list of references preceding the appendixes of this paper.

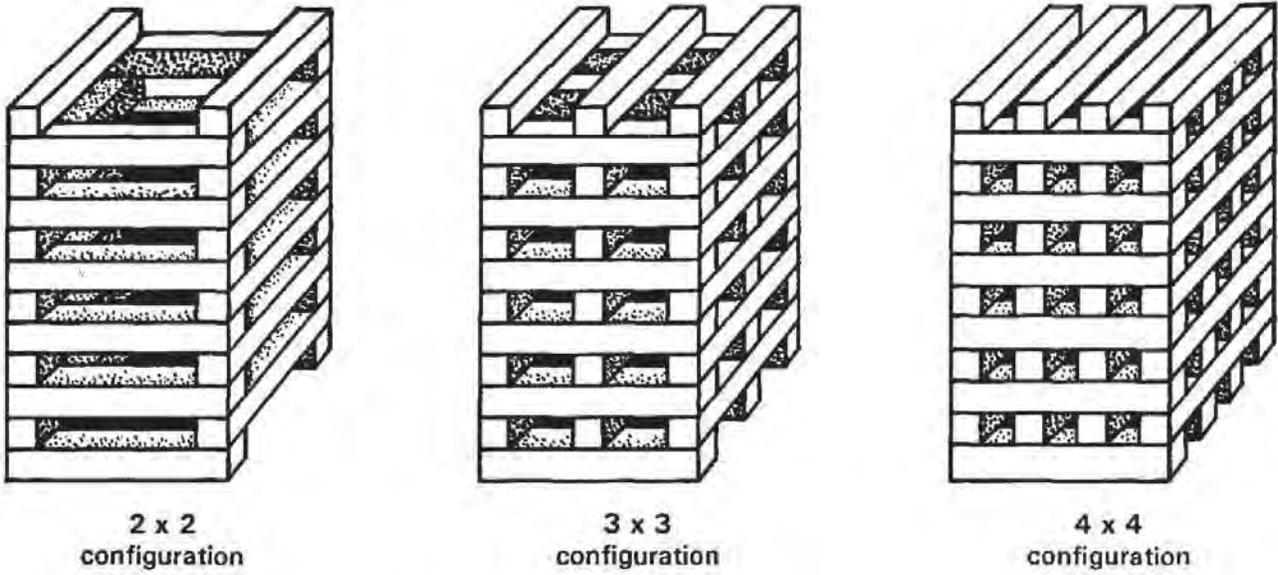


Figure 2.—Wood crib configurations.

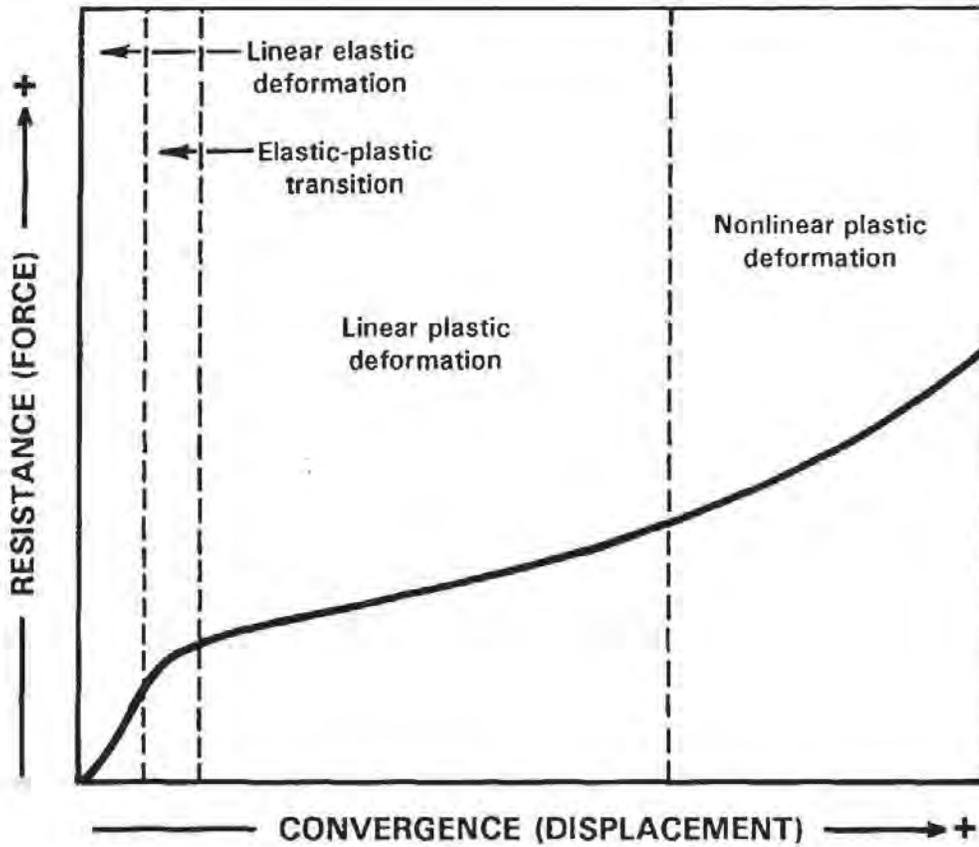


Figure 3.—Generalized force-displacement relationship for wood cribs.

## DESIGN CRITERIA AND CONSTRUCTION CONSIDERATIONS

Strength, stiffness, and stability are the criteria that must be met for an acceptable crib design. The strength of a crib is its capacity to support a load. Stiffness is a measure of the resistive force developed to an applied displacement. Stability is a measure of the capability of a structure to maintain equilibrium without sudden or severe loss of load capacity.

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 is maximized by increasing timber width, increasing the number of timbers per layer, and using a high-strength wood.

Stability depends most 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 becomes more dominant at larger strains. 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 hardness of many wood species are reported by the U.S. Department of Agriculture's Forest Service (3) and the American Society for Testing and Materials (4). Compressive strength and hardness values for wood species commonly used for mine timbers are indicated in table 1.

Factors to consider in wood crib design are summarized below.

### TIMBER DIMENSIONS

Timber cross sections may be square or rectangular. With rectangular cross sections, maximum stiffness is attained when the timbers are stacked to maximize the interlayer contact area. The placement of just a single layer of timbers with the smaller dimension in contact with the adjacent layers reduces the stiffness of the crib structure.

Timber length 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. The aspect ratio decreases as timber length increases. The effect of the timber length on crib performance is shown in figure 4. Generally, a reduction in the aspect ratio by using longer timbers increases the stability of the crib structure by increasing its resistance to buckling. This increase in stability preserves maximum crib stiffness.

Table 1.—Properties of common wood species used for mine timbers

Wood species	Compressive strength <sup>1</sup>		Average hardness <sup>2</sup>	
	N/cm <sup>2</sup>	psi	N	lb
<b>Hardwood:</b>				
Yellow birch <sup>3</sup> .....	498	723	4,537	1,020
Rock elm .....	698	1,012	5,026	1,130
Black locust .....	1,300	1,886	7,272	1,635
Black maple <sup>3</sup> .....	687	997	4,492	1,010
Red maple .....	473	686	3,670	825
Northern red oak <sup>3</sup> .....	681	987	5,093	1,145
Pin oak .....	813	1,179	5,738	1,290
White oak .....	765	1,109	5,383	1,210
Yellow poplar .....	324	470	2,180	490
<b>Softwood:</b>				
Douglas fir .....	533	773	3,816	585
Western larch .....	597	867	2,980	670
Jack pine .....	396	575	2,157	485
Lodgepole pine <sup>3</sup> .....	305	443	1,801	405
Ponderosa pine .....	412	597	1,735	390
Tamarack .....	482	699	2,157	485

<sup>1</sup>Unseasoned wood at 0.1016 cm (0.04 in) of displacement.

<sup>2</sup>Average of dry and unseasoned values.

<sup>3</sup>Species used for model development.

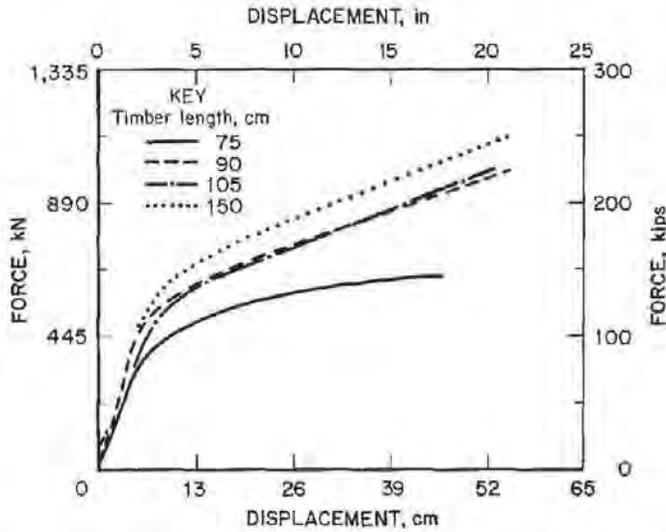


Figure 4.—Effect of timber length as a measure to control crib aspect ratio.

**MINING HEIGHT**

An increase in crib height reduces both stiffness and stability. These effects can be minimized by controlling the aspect ratio of the crib, as depicted in figure 4. The aspect ratio should be less than 4.3 to provide stable crib performance with linear plastic behavior through 20-pct strain. Cribs constructed with aspect ratios of less than 2.5 use more wood than is necessary to provide effective mine roof support.

**TIMBER CONSTRUCTION**

Wood cribs perform better when constructed with overhanging timbers. When the crib is constructed without overhanging timbers, the load is applied to the end of the timber. This reduces the strength and stiffness of the structure. Additionally, crib constructions without overhanging timbers are more susceptible to local shear failures of individual timbers (figure 5). These failures create unequal loading at the weakened layer and contribute to buckling of the crib structure. Overhanging timbers interlock when compressed, thereby reducing the effects of shear failures. Figure 6 shows that cribs constructed with overhanging timbers provide a 10- to 15-pct increase in crib resistance. The performance improvement is accomplished even though the aspect ratio is increased slightly. An overhang length of one-half the width of the timber is recommended.

**NUMBER OF TIMBERS PER LAYER**

The number of contact points in a crib construction equals the square of the number of timbers per layer.

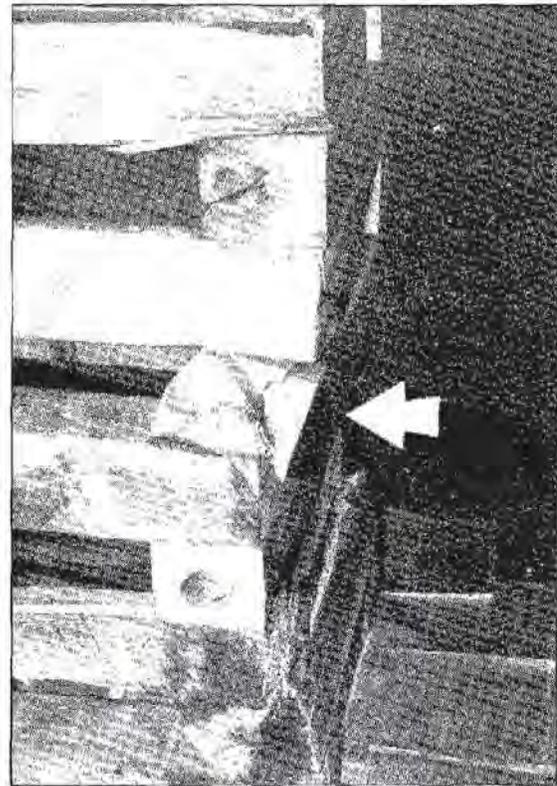


Figure 5.—Arrow indicates shear failure of a timber in a crib construction without overhanging timbers.

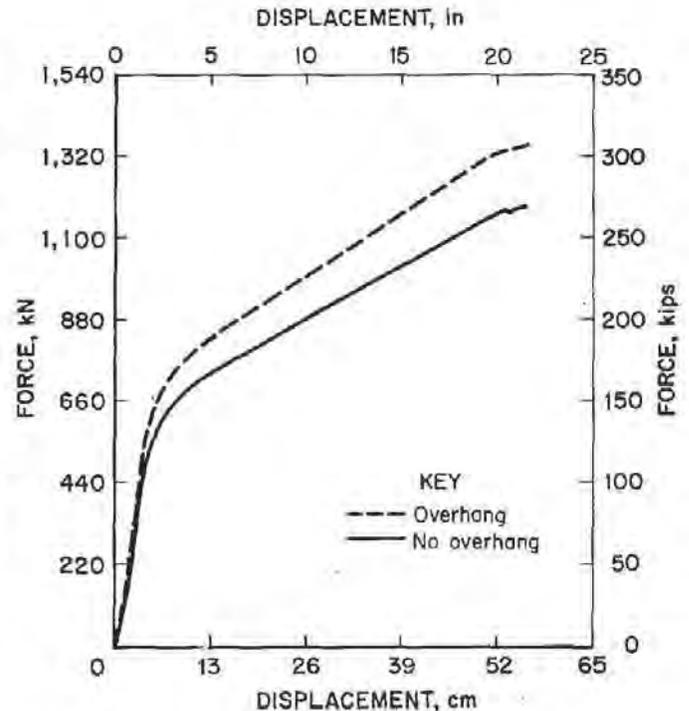


Figure 6.—This graph indicates the improved performance of cribs constructed with overhanging timbers.

Theoretically, the resulting increase in contact area will increase the capacity and the stiffness of the crib proportionately. However, a reduction in timber stiffness from this expectation is observed in multitimbered crib constructions when more than two timbers per layer are

used. This reduction stems from the increase in the percentage of loaded area and the reduced distance between the contact areas, which reduces the volume of unstressed wood that provides confinement to loaded sections.

## WOOD CRIB PERFORMANCE MODEL

Equation 1 represents the characteristic equation developed to predict the force-displacement behavior of wood cribs.<sup>5</sup> The compressive strength (perpendicular to the grain) and hardness of the wood species are the foundation of the Wood Crib Performance 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 also depends on the height of the structure. The plastic stiffness coefficient ( $K_p$ ) represents the stiffness of the crib structure during the linear plastic phase of deformation and is based on wood hardness. Adjustments in crib performance also include factors pertaining to (1) percentage of timber contact area, (2) aspect ratio, and (3) timber construction.

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

where  $F_{\text{Crib}}$  = crib resistance, kN,

$A$  = compressive strength coefficient, kN,

$K_p$  = plastic stiffness coefficient, kN/cm,

$\delta$  = displacement, cm,

OHFCT = overhanging timber factor,

HTFCT = height factor,

PCTFCT = percentage of contact area factor,

and ARFCT = aspect ratio factor.

The information required to apply the Wood Crib Performance Model is as follows: (1) the wood species, (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.

Some values of compressive strength are reported at the proportional limit, while other values are reported at 0.1016-cm (0.04-in) deflection. Values for green wood reported at the proportional limit must be converted to the equivalent value at 0.1016-cm (0.04-in) deflection to be used in the model by using equation 2.

$$CS_{0.1016} = 1.589 \times CS_{\text{PL}} + 29.26, \quad (2)$$

where  $CS_{0.1016}$  = compressive strength at 0.1016-cm (0.04-in) deflection,

and  $CS_{\text{PL}}$  = compressive strength at proportional limit.

Application of the Wood Crib Performance Model is described below. An example of the procedure is provided in appendix A of this paper.

1. Determine the interlayer contact area by multiplying the area per contact by the number of contacts per layer.

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

where  $\text{AREA}_{\text{Layer}}$  = interlayer contact area, cm<sup>2</sup>,

$\text{AREA}_{\text{Contact}}$  = area per contact, cm<sup>2</sup>,

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.

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

where  $A$  = compressive strength coefficient, kN,

STRENGTH = compressive strength of wood, N/cm<sup>2</sup>,

and  $\text{AREA}_{\text{Layer}}$  = interlayer contact area, cm<sup>2</sup>.

<sup>5</sup>The equations presented throughout this paper are restated in U.S. customary units in appendix B of this paper.

3. Determine the modulus of plasticity for the wood using the wood hardness (table 1) in equation 5a (with overhang) or equation 5b (without overhang).

$$E_p = 0.7178 \times \text{HARDNESS} - 730.9 \quad (5a)$$

(with overhang)

$$E_p = 0.6898 \times \text{HARDNESS} - 965.3 \quad (5b)$$

(without overhang)

where  $E_p$  = modulus of plasticity of mine timber, N/cm<sup>2</sup>,

and  $\text{HARDNESS}$  = wood hardness, N.

4. Determine the plastic stiffness of a single timber by multiplying the area of a single interlayer contact by the modulus of plasticity, then 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, kN/cm,

$E_p$  = modulus of plasticity of mine timber, N/cm<sup>2</sup>,

$\text{AREA}$  = area per contact, cm<sup>2</sup>,

and  $\text{THICKNESS}$  = timber thickness, cm.

5. Determine the stiffness of the crib structure during plastic deformation by multiplying the number of contacts per layer by the timber stiffness, then dividing by the number of layers.

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

where  $K_p$  = plastic deformation crib stiffness, kN/cm,

$K_t$  = timber stiffness, kN/cm,

$\text{CONTACTS}$  = number of contacts per layer,

and  $\text{LAYERS}$  = 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 significantly affected by these parameters.

*Height Factor (HTFCT)*

$$\text{HTFCT} = 0.6378 - 1.8134 \times 10^{-3} \times \text{Crib Height} \quad (8)$$

where  $\text{Crib Height}$  = Height of crib, cm.

*Percentage of Timber Contact Area Factor (PCTFCT)*

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

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

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

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

where  $\text{AREA}_{\text{pct}}$  = timber contact area, pct,

$\text{AREA}_{\text{Layer}}$  = interlayer contact area, cm<sup>2</sup>,

$\text{CONTACTS}$  = number of contacts per layer,

$\text{TIMBERS}$  = number of timbers per layer,

$\text{TW}$  = timber width, cm,

and  $\text{TL}$  = timber length, cm.

*Aspect Ratio Factor (ARFCT)*

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

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

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

where AR = aspect ratio,  
 HEIGHT = crib height, cm,  
 OVERHANG = overhang distance, cm,  
 TL = timber length, cm,  
 and TW = timber width, cm.

*Overhanging Timber Construction Factor (OHFCT)*

$$\text{OHFCT} = 0.9 \text{ without overhanging timbers} \quad (13a)$$

$$\text{OHFCT} = 1 \text{ with overhanging timbers} \quad (13b)$$

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

## MODEL LIMITATIONS

This mathematical model to predict wood crib performance is based on data from tests conducted under controlled laboratory conditions. The variables that were controlled during the investigation were the loading rate, wood species, timber length, structure height, number of timbers per layer, and whether the crib was constructed with or without overhanging timbers. When all of these parameters are known, the force-displacement relationship of open-box crib designs can be predicted within a 10-pct error through 20-pct strain. The accuracy of the prediction is limited by variation of these and other parameters.

### MIXED WOOD SPECIES

When cribs are constructed from mixed wood species, the model should be applied using the lowest compressive strength and hardness values of the wood species used. This approach will provide a conservative estimate of crib performance.

### STABILITY FACTORS

The stability of an open-box wood crib depends on several factors, of which the aspect ratio is the most significant. The model can successfully predict the performance of cribs with aspect ratios between 2 and 6; however, it is recommended that aspect ratios be controlled to a range of 2.5 to 4.3 in crib design. The aspect ratio can be controlled by selecting a timber length that is compatible with the crib height.

Construction of a crib without overhanging timbers also affects stability. Crib construction with contact established at the ends of the timbers decreases the aspect ratio, and will decrease the effective strength and stiffness of the timbers. Furthermore, this type of construction is susceptible to shear failure of the timbers, resulting in instability. The model does not predict the effect of shear failure instabilities.

### LOAD APPLICATION

The effects of time-dependent properties of wood are not predicted by the model. The conditions of load

application can significantly affect the performance of wood cribs. Different rates of load application, static loads, and static displacements all result in different crib responses.

Generally, crib resistance decreases as the rate of loading decreases. The model was developed from data where a constant rate of displacement of 1.27 cm (0.5 in)/min was applied to the crib structure. Tests on full-scale cribs at 0.127 cm (0.05 in)/min showed little difference from tests conducted at 1.27 cm (0.5 in)/min. However, underground convergence rates in coal mines of 0.0254 cm (0.01 in)/h to 0.0004318 cm (0.00017 in)/min have been associated with unstable mine roof conditions. Load application rates on this order may diminish the resistance provided by wood crib supports.

When a static load is applied to a wood crib, the crib will continue to deform (creep) to approximately twice the initial displacement. The rate of deformation is a function of the load on the structure. When the load is below the elastic limit of the wood, the rate of creep is very slow. When the load exceeds the elastic limit of the wood, the rate of creep increases.

When a displacement is applied to a wood crib, the initial resistive force can be predicted by the model. However, relaxation of the wood causes the resistance to decrease with time. The resistive force can be reduced by 30 pct after 1 h and by 50 pct after 48 h.

### NONLINEAR BEHAVIOR

The model does not predict nonlinear plastic behavior. For typical crib configurations, plastic deformation will become nonlinear at strains between 20 and 30 pct, depending on the moment of inertia and the aspect ratio of the structure. Generally, 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 2 and 6.

## SUPPORT SYSTEM DESIGN AND EMPLOYMENT

The goal in support system design is to select a crib configuration and placement strategy. The support system must resist strata loading within a displacement that will ensure the integrity of the immediate roof in the mine opening. Criteria for support design and employment are summarized below.

1. *Crib stiffness and capacity.*—Cribs should have sufficient stiffness and capacity to preserve the integrity of the mine roof and floor. This requires that the cribs develop sufficient capacity within a displacement that will offset strata loading and prevent deflection of the immediate roof beam to failure (figure 7). Critical beam loading and deflection can be estimated from equations 14 and 15, respectively. Strata loading is measured per centimeter of entry and is computed as the weight of material within the pressure arch surrounding the opening (figure 7). These estimates should be tempered by knowledge of caving height (roof fall cavities) and roof sag to more accurately identify force and displacement criteria for crib design. The maximum required capacity occurs when the immediate mine roof has no strength and the full weight of strata that are detached from stable roof structures must be supported by the crib.

$$F_{\text{Critical}} = \frac{4 \times t^2 \times \sigma}{3 \times L} \times 10^{-3}, \quad (14)$$

where  $F_{\text{Critical}}$  = critical loading of the roof beam, kN/cm,

$t$  = thickness of immediate roof beam, cm,

$\sigma$  = tensile strength of roof rock, N/cm<sup>2</sup>,

and  $L$  = length of roof beam, cm.

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

where  $\delta_{\text{Critical}}$  = critical displacement of roof beam, cm,

$\sigma$  = tensile strength of the roof rock, N/cm<sup>2</sup>,

$L$  = length of roof beam, cm,

$E$  = modulus of elasticity of roof rock, N/cm<sup>2</sup>,

and  $t$  = thickness of immediate roof beam, cm.

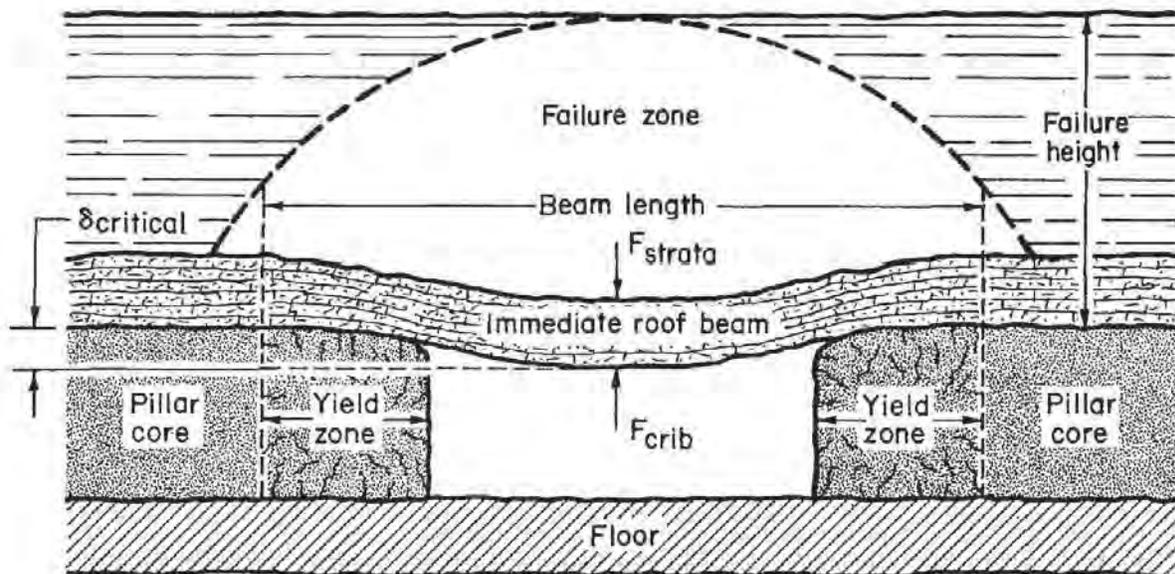


Figure 7.—Crib-strata interaction involving deflection of the immediate roof beam.  $\delta_{\text{critical}}$  = critical displacement of roof beam,  $F_{\text{strata}}$  = imposed strata load, and  $F_{\text{crib}}$  = crib resistance.

2. *Stability requirements.*—Cribs should remain stable and provide support through a displacement that includes roof deflection, coal pillar deformation, and floor heave. Crib stability is ensured by selecting the proper timber length for the mining height to maintain an aspect ratio of less than 4.3.

3. *Roof and floor contact pressures.*—The cribs should have adequate contact area to provide roof and floor contact pressures that are compatible with the strength of the immediate roof and floor. Contact pressure can be estimated by dividing the crib load by twice the interlayer contact area. Full timber length should not be used as an estimate of contact area, since the load distribution is not uniform along the timber.

4. *Crib spacing and employment cost.*—The cost of the support system will depend largely on how far apart the cribs can be spaced. Crib spacing is measured as the distance between cribs. It is determined by the roof load per centimeter of entry and the roof strength as a function of the critical displacement of the immediate roof in relation to the stiffness and capacity of the crib design. Each crib must support a section of roof within a displacement that will control the integrity of the roof. These requirements are expressed in equation 16. This spacing is limited by the capability of the roof to span without support.

$$\text{SPACE } (\delta_c) = \frac{F_{\text{Crib}} (\delta_{\text{Critical}})}{F_{\text{Strata}} - F_{\text{Critical}}} - \text{TL}, \quad (16)$$

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

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

$F_{\text{Strata}}$  = imposed strata load, kN/cm,

$F_{\text{Critical}}$  = critical beam load, kN/cm,

and  $\text{TL}$  = timber length, cm.

The employment cost is the material and labor costs required for the support system installation measured in dollars per centimeter of entry. It is calculated by adding the material and labor costs, then dividing by the crib spacing plus the timber length (see equation 17).

$$\text{EMPLOY COST} = \frac{\text{CONS COST}}{\text{SPACING} + \text{TL}}, \quad (17)$$

where  $\text{EMPLOY COST}$  = employment cost, \$ per cm of entry,

$\text{CONS COST}$  = cost to construct a crib, \$,

$\text{SPACING}$  = crib spacing, cm,

and  $\text{TL}$  = timber length, cm.

The equivalent cost spacing is the spacing that provides the same employment cost for all crib designs. It is determined from equation 18. Placement of cribs at distances greater than the equivalent cost spacing will provide savings in the cost of employment. The equivalent cost spacing is useful in comparing the advantages of multi-timbered configurations to 2x2 crib designs.

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

$$\frac{\text{CONS COST} - (\text{TL} \times \text{EMPLOY COST})}{\text{EMPLOY COST}}, \quad (18)$$

where  $\text{EQ (COST) SPACE}$  = equivalent cost spacing, cm,

$\text{CONS COST}$  = construction cost for single crib, \$,

$\text{TL}$  = timber length, cm,

and  $\text{EMPLOY COST}$  = employment cost per centimeter of entry, \$/cm.

The equivalent force spacing, where the support system resistance per centimeter of entry is equal, can be computed using equation 19. This equation can be used to compare alternative crib designs with a current support system.

$$\text{EQ (FORCE) SPACE} = \frac{F_{\text{Crib}} - (\text{TL} \times F_{\text{Supsys}})}{F_{\text{Supsys}}}, \quad (19)$$

where  $\text{EQ (FORCE) SPACE}$  = equivalent force spacing, cm,

$F_{\text{Crib}}$  = individual crib resistance at critical displacement, kN,

$F_{\text{Supsys}}$  = crib resistance per cm of mine entry, kN/cm,

and  $\text{TL}$  = timber length, cm.

## CONCLUSIONS AND RECOMMENDATIONS

The design and utilization 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 importance of the stiffness of the support structure should be carefully considered in designing wood cribs. Often, too much attention is given to the capacity of the support without recognizing the stiffness. It is the development of the support capacity within a specified displacement that is crucial to ground control. Therefore, efforts to maximize crib stiffness should be a design priority.

Proper construction methods are necessary to ensure optimum performance from crib support systems. Recommendations to maximize crib efficiency are summarized below.

1. Wood cribs should be constructed with overhanging timbers. The minimum recommended overhang distance is one-half the width of the timber. Overhang construction 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 those with similar compressive strength and hardness. This helps prevent differential compression of timbers in a single layer, which can contribute to buckling-induced failure.

3. The aspect ratio (height-to-width ratio) for wood crib construction should be between 2.5 and 4.3 to ensure stability through 20-pct strain and for efficient use of the wood timbers. Timber lengths should increase as the mining height increases to maintain an aspect ratio in this range.

4. Wood cribs should be constructed to maximize the interlayer contact area. Therefore, the wide side of the timber should be placed horizontally in the crib construction. This construction will provide maximum stability and support capacity.

5. The stiffness of wood cribs can be increased by increasing the number of timbers per layer or by increasing the width of the timber. Increasing the width of the timber should be given first priority, since additional timbers

per layer will increase the labor costs for construction. The increased stiffness will provide greater resistance at less displacement, which will improve ground control.

Application of the Wood Crib Performance Model has led to recommendations for wood crib utilization. These recommendations are summarized below.

1. Most wood crib systems in longwall gate roads employ one or two rows of 2×2 wood crib constructions placed 1.52 m (5 ft) apart. The example discussed in this report demonstrates that 3×3 and 4×4 crib configurations are more cost-effective than 2×2 configurations, provided they can be spaced at distances commensurate with their higher capacity advantage.

2. The equivalent cost spacing of a 3×3 and a 4×4 configuration compared with a 2×2 configuration on a 1.52-m (5-ft) spacing in a 2-m (80-in) thick coal seam is 2.7 m (8.7 ft) and 3.8 m (12.5 ft), respectively. Installation of the 3×3 or 4×4 configurations at greater distances than the equivalent cost spacing will provide a cost savings.

3. A single 3×3 wood crib will provide more capacity at less cost than a double row of 2×2 wood cribs. Therefore, a single row of 3×3 cribs should be used if the mine roof is sufficiently competent to remain stable. When the supported area needs to be increased owing to poor roof quality, consideration should be given to a rectangular 3×3 design where the long axis is employed across the entry. The rectangular design will increase roof coverage while preserving the capacity enhancements of the 3×3 configuration.

4. The stiffness of wood cribs increases as the height decreases. Therefore, if the mining height changes significantly, the crib spacing or design should be adjusted accordingly.

Wood cribs are likely to continue to be used extensively to improve ground control in underground coal mining. The information presented in this paper will enhance the efficient utilization of these support systems and will lead to a safer underground environment for mineworkers.

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## APPENDIX A.—WOOD CRIB DESIGN AND EMPLOYMENT EXAMPLES

### EXAMPLE 1: WOOD CRIB PERFORMANCE MODEL

The example below calculates the load-displacement relationship for a 203.2-cm (80-in) high, 3×3 crib constructed from northern red oak timbers with overhanging ends. The timber size is 13×15×76 cm (5×6×30 in). The compressive strength (perpendicular to the grain) and hardness for the northern red oak are 680.5 N/cm<sup>2</sup> (987 psi) and 5,093 N (1,145 lb), respectively (see table 1).

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

$$\begin{aligned} \text{AREA}_{\text{Layer}} &= (15.24 \times 15.24) \text{ cm}^2 \\ &\times (3 \times 3) \text{ CONTACTS} = 2,090 \text{ cm}^2 \quad (\text{A-1}) \end{aligned}$$

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

$$A = 680.5 \text{ N/cm}^2 \times 2,090 \text{ cm}^2 \times 10^{-3} = 1,422 \text{ kN} \quad (\text{A-2})$$

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.

$$E_p = 0.7178 \times 5,093 \text{ N} - 730.87 = 2,925 \text{ N/cm}^2 \quad (\text{A-3})$$

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

$$\begin{aligned} K_t &= \frac{2,925 \text{ N/cm}^2 \times (15.24 \times 15.24) \text{ cm}^2}{12.70 \text{ cm}} \\ &\times 10^{-3} = 53.5 \text{ kN/cm} \quad (\text{A-4}) \end{aligned}$$

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

$$\begin{aligned} K_p &= \frac{53.5 \text{ kN/cm} \times 9 \text{ CONTACTS}}{16 \text{ LAYERS}} \\ &= 30.1 \text{ kN/cm} \quad (\text{A-5}) \end{aligned}$$

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

#### Height Factor (HTFCT)

The height factor is computed as 0.269 using equation 8.

$$\begin{aligned} \text{HTFCT} &= 0.6378 - 1.8134 \times 10^{-3} \times 203.2 \text{ cm} \\ &= 0.269 \quad (\text{A-6}) \end{aligned}$$

#### Percentage of Timber Contact Area Factor (PCTFCT)

The percentage of timber contact area is computed from equation 10b as 60 pct for the 3×3 configuration using 13×15×76-cm (5×6×30-in) timbers. Since this is greater than 55 pct, PCTFCT equals 0.9.

$$\text{AREA}_{\text{pct}} = \frac{15.24 \times 3}{76.2} \times 100 = 60 \text{ pct} \quad (\text{A-7})$$

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

#### Aspect Ratio Factor (ARFCT)

The aspect ratio for the 203-cm (80-in) high crib constructed from 76-cm (30-in) long timbers with 7.62 cm (3 in) of overhang on each end is computed as 4.44, which makes ARFCT equal to 0.94.

$$\text{AR} = \frac{203.2}{76.2 - (2 \times 7.62) - 15.24} = 4.44 \quad (\text{A-9})$$

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

#### Overhanging Timber Construction Factor (OHFCT)

Since the crib is constructed with overhanging timbers, OHFCT equals 1. Therefore, the following equation represents the force-displacement relationship for this crib. Figure A-1 compares the Wood Crib Performance Model prediction to a full-scale test of a 3×3 crib in the mine roof simulator at the USBM's Pittsburgh Research Center.

$$\begin{aligned} F_{\text{Crib}} (3 \times 3) &= 1,422 \times 1 \times 0.9 \times (1 - e^{-0.269 \times \delta}) \\ &\quad + 0.9 \times 0.94 \times 30.1 \times \delta \text{ kN} \quad (\text{A-11}) \end{aligned}$$

$$\begin{aligned} F_{\text{Crib}} (3 \times 3) &= 1,278.9 \times (1 - e^{-0.269 \times \delta}) \\ &\quad + 25.5 \times \delta \text{ kN} \quad (\text{A-12}) \end{aligned}$$

## EXAMPLE 2: EMPLOYMENT ANALYSIS

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 12.7×15.24×76.2-cm (5×6×30-in) northern red oak timbers and is employed in single-row arrangement at 152.4-cm (5-ft) spacing in a 203.2-cm (80-in) coal seam. Mine experience has shown that roof sag (deflection) must be controlled to less than 6.1 cm (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 6.1 cm (2.4 in) of displacement is 587.1 kN (132 kips), which translates to 2.57 kN per cm (17.6 kips per ft) of entry for a 152.4-cm (5-ft) crib spacing.

$$F_{\text{Crib}} (2 \times 2) = 632.1 \times (1 - e^{-0.269 \times \delta}) + 12.6 \times \delta \quad (\text{A-13})$$

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 4.3 for the crib structure. On this basis, 76.2-cm (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 A-2. Using these equations to compute the crib resistance at 6.1 cm (2.4 in) of displacement, it is found from equation 19 that the 3×3 crib design can be spaced at 384 cm (12.6 ft) and provide the same resistance to roof loading as the current 2×2 design. Likewise, the 4×4 design can be spaced at 744 cm (24.4 ft) and provide equal resistance.

$$F_{\text{Crib}} (3 \times 3) = 1,278.9 \times (1 - e^{-0.269 \times \delta}) + 25.5 \times \delta \quad (\text{A-14})$$

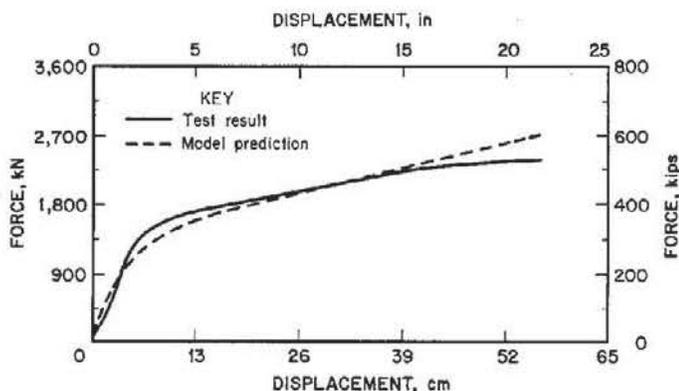


Figure A-1.—Comparison of Wood Crib Performance Model prediction with full-scale testing of 3×3 crib in the USBM's mine roof simulator.

$$F_{\text{Crib}} (4 \times 4) = 2,276 \times (1 - e^{-0.269 \times \delta}) + 45.5 \times \delta \quad (\text{A-15})$$

$$\begin{aligned} \text{EQ (FORCE) SPACE (3} \times \text{3)} &= \frac{1,183.2 - (76.2 \times 2.57)}{2.57} \\ &= 384 \text{ cm} \quad (\text{A-16}) \end{aligned}$$

$$\begin{aligned} \text{EQ (FORCE) SPACE (4} \times \text{4)} &= \frac{2,108.4 - (76.2 \times 2.57)}{2.57} \\ &= 744 \text{ cm} \quad (\text{A-17}) \end{aligned}$$

Since 305 cm (10 ft) is considered the maximum acceptable unsupported roof span, the 3×3 design at 305-cm (10-ft) spacing is chosen as the optimum crib design and employment. This design will provide a cost savings of 10 pct with over 20 pct more support force.

$$\begin{aligned} \text{EMPLOY COST (2} \times \text{2)} &= \frac{44}{152.4 + 76.2} \\ &= \frac{\$0.1926}{\text{cm}} \quad (\text{A-18}) \end{aligned}$$

$$\begin{aligned} \text{EMPLOY COST (3} \times \text{3)} &= \frac{66}{304.8 + 76.2} \\ &= \frac{\$0.1732}{\text{cm}} \quad (\text{A-19}) \end{aligned}$$

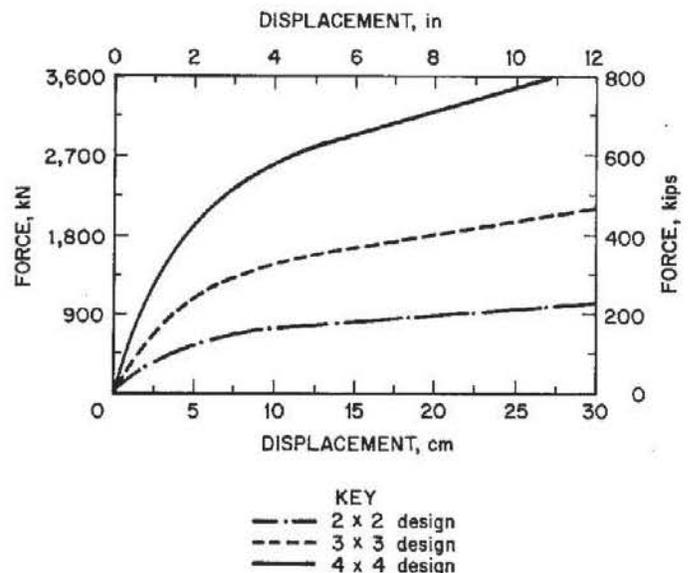


Figure A-2.—Comparison of 2×2, 3×3, and 4×4 wood crib performances.

## APPENDIX B.—EQUATIONS IN U.S. CUSTOMARY UNITS

Restated below are the equivalent equations from the main body of this paper in U.S. customary units.

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

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

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

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

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

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

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

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

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

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

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

$$\text{AREA}_{\text{pct}} = \frac{\text{AREA}_{\text{Layer}}}{\text{CONTACTS}} \times \frac{\text{TIMBERS}}{\text{TW} \times \text{TL} \times 12} \times 100 \quad (\text{B-10a})$$

$$\text{AREA}_{\text{pct}} = \frac{\text{TW} \times \text{TIMBERS}}{\text{TL} \times 12} \times 100 \quad (\text{B-10b})$$

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

$$\text{ARFCT} = 1 \text{ when } \text{AR} \leq 4.3 \quad (\text{B-11b})$$

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

$$\text{OHFCT} = 0.9 \text{ without overhanging timbers} \quad (\text{B-13a})$$

$$\text{OHFCT} = 1 \text{ with overhanging timbers} \quad (\text{B-13b})$$

$$F_{\text{Critical}} = \frac{4 \times t^2 \times \sigma}{3 \times L} \times 12 \times 10^{-3} \quad (\text{B-14})$$

$$\delta_{\text{Critical}} = \frac{5 \times \sigma \times L^2}{24 \times E \times t} \quad (\text{B-15})$$

$$\text{SPACE} (\delta_c) = \frac{F_{\text{Crib}} (\delta_{\text{Critical}})}{F_{\text{Strata}} - F_{\text{Critical}}} - \text{TL} \quad (\text{B-16})$$

$$\text{EMPLOY COST} = \frac{\text{CONS COST}}{\text{SPACING} + \text{TL}} \quad (\text{B-17})$$

EQ (COST) SPACE =

$$\frac{\text{CONS COST} - (\text{TL} \times \text{EMPLOY COST})}{\text{EMPLOY COST}} \quad (\text{B-18})$$

$$\text{EQ (FORCE) SPACE} = \frac{F_{\text{Crib}} - (\text{TL} \times F_{\text{Supsys}})}{F_{\text{Supsys}}} \quad (\text{B-19})$$

Use ft for: SPACE ( $\delta_c$ ), SPACING, EQ (COST) SPACE, and EQ (FORCE) SPACE.

Use inches for:  $\delta$ , THICKNESS, Crib Height, TW, TL, HEIGHT, OVERHANG, t, L, and  $\delta_{\text{Critical}}$ .

Use in<sup>2</sup> for: AREA<sub>Layer</sub>, AREA<sub>Contact</sub>, and AREA.

Use kips for: F<sub>Crib</sub> and F<sub>Crib</sub> ( $\delta_{\text{Critical}}$ ).

Use kips/ft for: F<sub>Strata</sub>, F<sub>Critical</sub>, and F<sub>Supsys</sub>.

Use kips/in for: K<sub>p</sub> and K<sub>t</sub>.

Use lb for: HARDNESS.

Use psi for: CS<sub>PL</sub>, STRENGTH, E<sub>p</sub>,  $\sigma$ , and E.

Use \$/ft for: EMPLOY COST.

Special Publication 01-94

# New Technology for Longwall Ground Control

Proceedings: U.S. Bureau of Mines Technology Transfer Seminar

Compiled by Christopher Mark, Robert J. Tuchman,  
Richard C. Repsher, and Catherine L. Simon



**UNITED STATES DEPARTMENT OF THE INTERIOR**  
**Bruce Babbitt, Secretary**

**BUREAU OF MINES**

Cover Photograph: The U.S. Bureau of Mines has developed highly practical technologies for maintaining effective ground control in the hazardous tailgate entries of longwall mining systems, which will significantly improve the safety of the Nation's underground mineworkers. (Photo: Alan A. Campoli, Pittsburgh Research Center, U.S. Bureau of Mines)