APPLICATION OF PARAMETRIC COLUMN ANALYSIS TO EVALUATE ECCENTRIC LOADING CONDITIONS ON PROP SUPPORT PERFORMANCE

D. Gearhart, NIOSH, Pittsburgh, PA

Abstract

Full-scale tests are conducted on mine roof supports using protocols developed by the National Institute for Occupational Safety and Health (NIOSH) using the unique capabilities of the Mine Roof Simulator (MRS). These protocols simulate the loading conditions that the support will be exposed to in an underground mine to determine the performance capabilities and limitations of the support. Some tests are conducted with rigid boundary conditions, creating uniform contact and near ideal axial loading conditions. These tests are used to determine the ultimate performance potential of a support, including the strength, stiffness, and stability. For prop supports where stability is a critical design issue, tests are implemented to induce buckling by a modified end condition, eccentric contact, or biaxial loading. It is important to determine the cpacity of the support design when the support is subjected to unpredictable loading conditions. This paper examines the effect of end conditions and load profiles on prop support performance and applies a new analysis methodology based on eccentric loading to determine a factor of safety for load capacity. Recommendations for installation practices that minimize eccentricity and therefore preserve capacity are also provided.

Introduction

The evaluation of standing supports at the National Institute for Occupational Safety and Health's (NIOSH) Mine Roof Simulator (MRS) has been an ongoing research effort with a significant record of success. The objective of this research is to eliminate hazards and injuries that result from roof falls in underground mines, and to reduce or eliminate material handling injuries that occur during installation of these support systems. In order to continue the advance toward these objectives, a complete understanding of the interaction between the support and the strata is necessary. One component of that relationship is the behavior or response of the standing supports. The MRS is a unique biaxial press that can replicate the loads and displacements that standing supports are subjected to in the underground environment.

The protocol used at the MRS for testing standing supports first establishes the baseline performance under controlled loading conditions. This initial phase of testing is extremely beneficial because design flaws or defects are exposed during the laboratory investigation, rather than during an extended and uncontrollable underground trial. This reduces the exposure of miners to unproven support technology and avoids product development delays for the manufacturers.

Underground, variable boundary conditions can significantly decrease the capacity of prop supports from that measured under uniform loading conditions in the laboratory. These eccentric loading conditions are replicated during the second phase of the MRS testing protocol, which is intended to reveal design and performance limitations of the support product under adverse, non-axial loading. While the full-scale tests conducted in the MRS effectively reveal performance limitations for a support product, an analysis methodology must be developed to identify critical design parameters and quantify the limitations of the support within its full operational range.

For structural columns, historical analysis methods classify their design by length and use different equations to predict the buckling stress. In this paper, an alternative analysis method is proposed that allows for determination of prop support capacity based on a stability parameter and an eccentricity factor. The stability parameter is dependent on the geometric and material properties of the structure. The eccentricity factor is dependent on the boundary conditions and load application. This analysis method can provide a direct measure of the strength performance of the supports once the stability and eccentricity are determined. Finally, prop support capacity can be optimized with installation practices that reduce the eccentricity of the loading.

MRS Testing Protocol

The testing protocol used to evaluate standing support in the MRS is designed to establish the baseline performance for a support, and then to induce realistic loading conditions that can degrade the capacity. Tests with modified boundary conditions and biaxial loading are used to evaluate the effect of eccentric loads on performance. All tests are conducted in the displacement-controlled mode of operation (Barczak 2000).

- **Loading Induced Through Vertical Displacement -** This loading profile applies a uniaxial vertical displacement to the support and is used to measure the baseline performance. These test results determine the strength, stiffness, roof and floor bearing pressures, and general stability of the support. On new support concepts that are under development, design flaws are frequently discovered during these tests. The rate of load application depends on the stiffness or yielding characteristics of the specimen.
- **Loading Induced Through Biaxial Displacement -** The biaxial loading profile is used to further evaluate the stability of the support when subjected to eccentric loads. These tests are typically conducted with ratios of 3:1 or 2:1 vertical to horizontal displacement. The performance of the support during this test protocol can be acutely affected by the boundary conditions on the support.

Boundary Conditions

Baseline tests use full, uniform contact between the ends of the support and the upper and lower platens of the simulator. This minimizes eccentricity since it maintains the best alignment of the load vector with the axis of the support throughout the test. Any eccentricity that exists or develops in this test condition is the result of material anomalies, misalignment of prop elements, or ends that are not perpendicular to the axis of loading. The addition of headboards, footboards, and prestressing devices are included in the second phase of testing to introduce potential eccentricity that affects the strength, stiffness, and stability of the support system. The objective is to evaluate the support under controlled eccentric load conditions to determine the performance limitations.

Performance Assessment Criteria

Support designs are assessed relative to three primary performance factors: (1) strength, (2) stiffness, and (3) stability. These three parameters are evaluated for standing supports that are subjected to displacements in the laboratory that realistically simulate the underground conditions.

- **Strength** - The strength of a roof support generally refers to its ultimate capacity. The strength of prop supports is dependent on the stability of the structure and the eccentricity of the loading. All supports are tested to failure to determine the peak capacity of the support.

- **Stiffness** - Stiffness is a measure of how quickly a passive support develops its load carrying capacity. The stiffness is determined by measuring the change in support load as a function of the applied displacement.
- **Stability** - Stability is a measure of the capacity of the support to maintain equilibrium under changing load conditions. The stability of a support structure is affected by several parameters. These include the following: (1) characteristics and material properties of the specimen, (2) aspect or slenderness ratio of the support, (3) boundary conditions established at the roof and floor contact, (4) orientation of the load application, and (5) design of the yield mechanism.

Crib versus Prop Performance Assessment

The behavior differences between crib and prop supports can be traced directly to the stability of the structures. If the structure is very stable, or resistant to buckling like a crib, the material properties control the strength and stiffness. The performance of these structures is characterized by support capacity equal to the material strength times the loading area. However, if the structure is susceptible to buckling, then stability controls the performance. Prop supports behave like columns that are susceptible to buckling, therefore the failure stress is much less than the material yield strength. In general, most mining props have slenderness ratios of less than 60, placing them in the range where buckling behavior is the result of a combination of stability and elastic material response.

Prop Support Performance Analysis

Historically, columns have been classified by length, and the buckling strength of long, slender columns is estimated by the Euler critical stress, which is well below the material compressive yield strength.

$$\sigma_{cr} = E \times \left(\frac{\pi}{\rho}\right)^2 \qquad (1)$$

Where: σ_{cr} = Euler's critical stress, psi
E = modulus of elasticity, psi and
ρ = slenderness ratio.

It is interesting to note that the load bearing capacity of long, slender columns is dependent on the elasticity of the material and the area moment of inertia, not on the compressive yield strength (Timoshenko 1949). Short and intermediate columns, which are typical of mine props, are more stable and their capacity is limited by the material strength. The capacity of these columns can be estimated using empirical design equations like the JB Johnson formula.

$$\sigma_{cr} = \sigma_y \left[1 - \frac{1}{2}\left(\frac{\rho}{C}\right)^2\right] \qquad (2)$$

Where: σ_{cr} = JB Johnson critical stress, psi
σ_y = material yield strength, psi
ρ = slenderness ratio, psi and
C = critical slenderness ratio.

The relationship among the column buckling load, moment and deflection can also be described by the Universal Column Formula (Dishongh, 2002) based on the concept of combined stress from axial loading and bending. The Euler and JB Johnson curves are shown in figure 1.

The second important factor affecting the ultimate capacity of columns is the end conditions. A column with pinned ends and a slenderness ratio of 100 will theoretically fail at 30 percent of the material yield strength, while the same column with fixed ends provides a slenderness ratio of 50 and will fail at nearly 80 percent of the material strength (see figure 1). This difference is because pinned end columns cannot resist the rotational moments that occur when the column begins to buckle, whereas the fixed end columns can resist these moments.

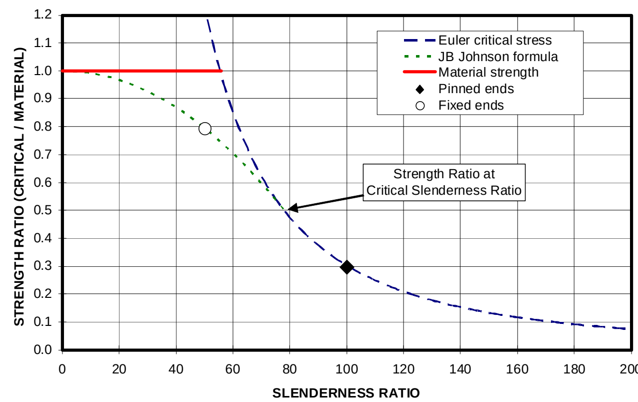

Figure 1. Empirical design equations for column stress.

Parametric Column Analysis

Conventional analysis of buckling is based on an idealized "perfect" column where pure elastic buckling can be defined. An alternative parametric analysis method that simplifies the interaction between strength and stability has been proposed (Wright 1999). Parametric Column Analysis complements the evaluation of underground support systems because: (1) it provides a quantifiable measure of the stability of the support and (2) the effect of unpredictable end conditions and eccentric loading that directly affect the strength and stiffness of props is measured in this analysis. This approach assumes that "imperfections" in material properties or fabrication and installation practices cause eccentricity that invariably reduces the load carrying capacity predicted by the idealized elastic buckling theory. For example, prop supports are typically constructed from multiple elements that work together to form a "composite" structure. The supports also have a variety of hardware or other materials used on the ends of the prop to establish contact and to distribute the support loads to the mine roof and floor. These features alter the ideal uniform loading conditions assumed in the conventional theory and create eccentric loading conditions that decrease the capacity of the support.

Column engineering practices typically use a design load and a factor of safety to develop a solution to ensure that the column will not fail. The values for the factor of safety and the assumed eccentricity contribute to robust designs that meet these requirements. However, the underground mining environment presents a more difficult problem for the support system designer. The loads or deflections that will be applied to the supports underground are for the most part unknown, so the requirements for the design are based on experience of what works and what does not. For prop supports, eccentric loads and indefinite boundary conditions will reduce the capacity of the supports and these conditions must be properly considered in the final design analysis. The proposed analysis method will assist in the development of useful values for eccentricity that can be used in design to improve the performance and reliability of prop support systems.

The input values needed for this analysis of MRS test results fall into three categories: (1) material properties, (2) geometric parameters, and (3) external loading conditions. The material properties are the modulus of elasticity and the compressive strength. The geometric parameters are the length, cross-sectional area, minimum area moment of inertia, and the maximum fiber distance. The properties of the external load are the magnitude, boundary conditions and initial eccentricity. Using these values, the radius of gyration, slenderness ratio, Euler critical buckling stress and the direct compressive stress are calculated. Finally, the parameters required for the analysis reduce to three dimensionless values:

- **Stability Parameter** - The stability parameter, •, is the ratio of the direct stress caused by axial loading to the critical buckling (Euler) stress. The stability parameter is a measure of the tendency towards stability failure. This parameter cannot exceed unity. It can be calculated for any support structure as shown in equation 3, where the maximum direct stress value can be defined as the material compressive strength. The advantage of the stability parameter for evaluation is that it is completely dependent on the material properties and geometric dimensions of the structure and does not require testing to be determine.

$$\psi = \frac{\sigma_{\text{direct}}}{\sigma_{\text{critical}}} \quad (3)$$

Where: Ψ = stability parameter,
σ_{direct} = sum of the axial and bending stress, psi and
$\sigma_{critical}$ = Euler critical buckling stress, psi.

- **Strength Parameter** - The strength parameter, θ, is the ratio of the direct compressive stress to the material compressive stress. The strength parameter measures the ultimate load capacity of the prop without loss of stability. Where actual test results are applied, the strength parameter is calculated as the ratio of the applied direct stress at failure to the material strength. As such, this parameter cannot exceed unity.

$$\theta = \frac{\sigma_{\text{direct}}}{\sigma_{\text{material}}} \quad (4)$$

Where: θ = strength parameter,
σ_{direct} = sum of the axial stress and bending stress, psi and
$\sigma_{material}$ = material compressive strength, psi.

- **Eccentricity Ratio** - The eccentricity ratio, •, reflects the severity of the imperfections or offset load. The value, as shown in equation 5, is the ratio of the actual eccentricity of the applied load to the maximum eccentricity that would cause no tensile stress by bending of the column. One challenge in design is selecting a reliable value for the initial eccentricity as shown in figure 2.

$$\eta = \frac{e \times y}{r^2} \quad (5)$$

Where: η = eccentricity ratio,
e = initial maximum eccentricity, in
y = extreme fiber distance, in
r = radius of gyration, in.

For the analysis presented in this paper, η is computed from Ψ and θ to solve for the eccentricity, e. Beam deflection theory is used to derive an equation that describes the relationship among these three parameters. For a straight column with a constant initial offset, as shown in figure 2, the equation is:

$$\frac{1}{\theta} = 1 + \eta \times \sec\left(\frac{\pi}{2} \times \sqrt{\psi}\right) \quad (6)$$

For analysis, this equation is rearranged to calculate η, thus:

$$\eta = \left(\frac{1}{\theta} - 1\right) \times \cos\left(\frac{\pi}{2} \times \sqrt{\psi}\right) \quad (7)$$

The strength-stability loci for different values of the eccentricity ratio are plotted on the chart shown in figure 3. The black diamond on the chart shows that for a support with a stability parameter of 0.75 and an eccentricity ratio of 0.2, the strength parameter is 0.5. This means that this prop will achieve only 50 percent of its ideal full load capacity. The chart demonstrates the importance of minimizing the stability parameter and the eccentricity ratio to maximize the strength performance for prop design and installation. Therefore, it is recommended that prop supports be designed with a stability factor •, less than 0.75 for their entire usable height range, and eccentric loading should be minimized. The following example will demonstrate the Parametric Column Analysis method using MRS test data to calculate the initial eccentricity.

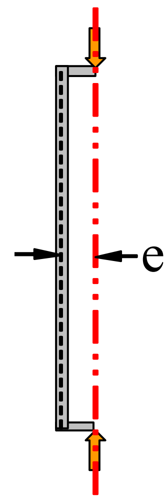

Figure 2. Initial eccentricity is the distance from the load axis to the unloaded column axis.

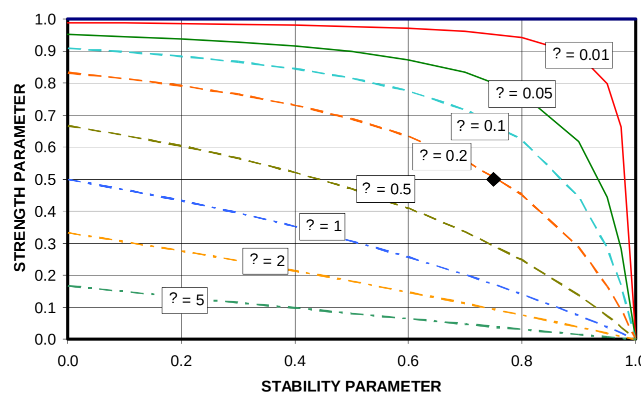

Figure 3. Loci of strength parameter versus stability parameter by eccentricity ratios.

Parametric Column Analysis Computations

This example of Parametric Column Analysis is presented to demonstrate the evaluation of the performance of an 11-foot tall, adjustable-height, non-yielding prop of the design shown in figure 4. The height-adjusting spindle is at its full extension of one foot. This specimen was tested in the MRS and the peak support capacity was measured as 111.8 kips (55.9 tons). The prop failed by buckling in the pipe section. The objective of this analysis is to demonstrate the method for calculation of the initial eccentricity for this test condition, which can then be used in subsequent evaluations of this prop design.

The first step of the analysis is to calculate the stability parameter, Ψ, using equation 3 for the prop at its ultimate capacity. The next step is to calculate the strength parameter, θ, using equation 4 with the direct applied stress (force/area) measured during testing, divided by the material strength. The values for the stability and strength parameters are then used to calculate the eccentricity ratio, η, using equation 7, and finally the initial eccentricity, e, using equation 8.

$$e = \frac{\eta \times r^2}{y} \quad (8)$$

Where: e = initial eccentricity, in,
η = eccentricity ratio,
r = radius of gyration, in, and
y = extreme fiber distance, in.

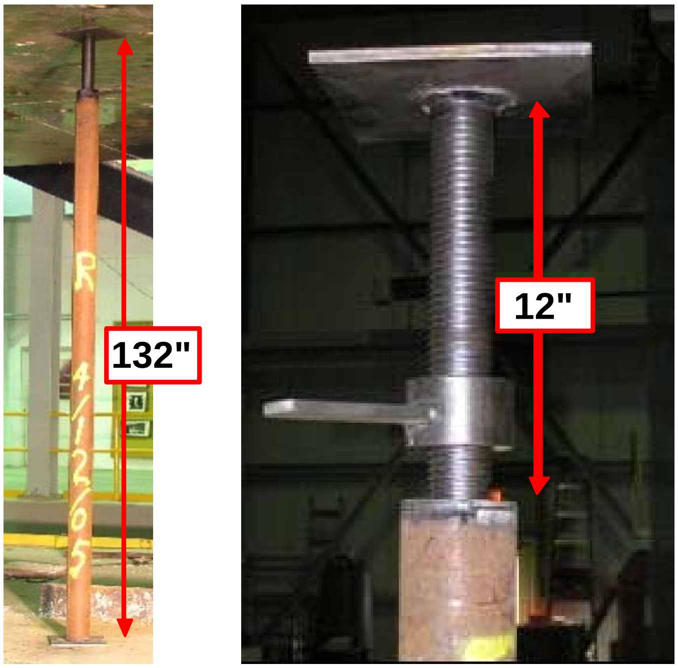

Figure 4. An adjustable height prop with detail of the spindle at the top end of the prop.

Full Prop Analysis: First assume that the spindle section of the prop is stronger than the pipe section, and therefore will behave as an extension of the pipe. With this assumption, the pipe will buckle at a critical load that is lower than the critical load of the spindle.

Given:	Total height (pipe and spindle):	132 in
	Pipe outer diameter:	3.563 in
	Pipe wall thickness:	0.254 in
	Material yield strength:	73 ksi
	Modulus:	29 E 6 psi

The area moment of inertia, radius of gyration and slenderness ratio are needed to compute the Euler buckling strength for the specimen.

Area:

$$A = \frac{\pi}{4} \times \left(3.563^2 - 3.055^2\right) = 2.640 \text{ in}^2$$

Area moment of inertia:

$$I = \frac{\pi}{4}\left[\left(\frac{3.563}{2}\right)^4 - \left(\frac{3.055}{2}\right)^4\right] = 3.635 \text{ in}^4$$

Radius of gyration: $r = \sqrt{(3.635 \text{ in}/2.64 \text{ in}^2} = 1.173 \text{ in}$

End condition factor: K = 0.5 (Column ends are fixed)

Effective length: L_{eff} = 132 in x 0.5 = 66 in

Slenderness ratio:

$$\rho = \frac{66 \text{ in}}{1.173 \text{ in}} = 56.258$$

Critical stress:

$$\sigma_{cr} = 29 \text{ E } 6 \times \left(\frac{\pi}{56.258}\right)^2 = 90.4 \text{ ksi}$$

Stability parameter:

$$\psi = \frac{73 \text{ ksi}}{90.4 \text{ ksi}} = 0.807$$

Spindle Analysis: Next, assume that the spindle is weaker than the pipe section and that the spindle will fail first.

Given:	Spindle height:	12 in
	Outer diameter:	2.000 in
	Wall thickness:	1.000 in (Solid section)
	Material yield strength:	73 ksi
	Modulus:	29 E 6 psi

Using the same calculations as before:

Area:

$$A = \frac{\pi}{4} \times \left(2.000^2 - 0.000^2\right) = 3.142 \text{ in}^2$$

Area moment of inertia:

$$I = \frac{\pi}{4} \times \left[\left(\frac{2.000}{2}\right)^4 - \left(\frac{0.000}{2}\right)^4\right] = 0.785 \text{ in}^4$$

Radius of gyration: $r = \sqrt{\left(0.785 \text{ in}^4/3.142 \text{ in}^2\right)} = 0.500 \text{ in}$

End condition factor: K = 2.0 (One end free)

Effective length: L_{eff} = 12 in x 2.0 = 24 in

Slenderness ratio:

$$\rho = \frac{24 \text{ in}}{0.500 \text{ in}} = 48$$

Critical stress:

$$\sigma_{cr} = 29 \text{ E } 6 \times \left(\frac{\pi}{48}\right)^2 = 124.2 \text{ ksi}$$

Stability parameter:

$$\psi = \frac{73 \text{ ksi}}{124.2 \text{ ksi}} = 0.588$$

Component Failure Assessment: The values calculated for the stability parameter, Ψ, indicate that the whole prop is less stable than the spindle section (Ψ_{prop} = 0.807 > $\Psi_{spindle}$ = 0.588), meaning that the pipe will fail at a lower load. This was confirmed by the laboratory test where the buckling occurred in the pipe section.

Determine Load Eccentricity: Using the laboratory load measurement, calculate the value of the strength parameter, θ_{pipe}, for the pipe:

$$\theta_{pipe} = \left(\frac{\sigma_{direct}}{\sigma_{material}}\right) = \frac{\left(111{,}800 \text{ lbs}/2.640 \text{ in}^2\right)}{73{,}000 \text{ psi}} = 0.580$$

Using equation (7), η calculated as 0.115.

$$\eta = \left(\frac{1}{\theta} - 1\right) \times \cos\left(\frac{\pi}{2} \times \sqrt{\psi}\right) = \left(\frac{1}{0.580} - 1\right) \times \cos\left(\frac{\pi}{2} \times \sqrt{0.807}\right)$$

Using equation (8), solve for the eccentricity, e:

$$e = \frac{\eta \times r^2}{y} = \frac{0.115 \times 1.173^2}{(3.563/2)} = 0.089 \text{ in}$$

Compute Spindle Capacity: Using this same initial eccentricity for the spindle; compute the strength factor for the spindle.

$$\eta = \frac{e \times y}{r^2} = \frac{0.089 \times 1}{0.500^2} = 0.356$$

$$\frac{1}{\theta} = 1 + \eta \times \sec\left(\frac{\pi}{2} \times \sqrt{\psi}\right) = 1 + 0.356 \times \sec\left(\frac{\pi}{2} \times \sqrt{0.588}\right)$$

$$\theta_{spindle} = 0.502$$

Analysis Summary: The results of these calculations indicate that under laboratory conditions, the combined misalignment of prop components, material flaws and imperfect boundary conditions resulted in an initial eccentricity of 0.089 inches from the central axis of the prop. The spindle buckling load under these conditions is calculated to be 115.1 kips, which is slightly higher than the buckling load for the pipe, 111.8 kips, at this eccentricity. This shows that the value for the initial eccentricity can be determined from analysis of MRS test results and that this parametric method can be used to assess prop support designs and underground installation practices.

DETERMINATION OF ECCENTRICITY IN PROP SUPPORT LOADING

A program to assist a manufacturer to develop a new prop support was undertaken by NIOSH that provided an ideal opportunity to evaluate the proposed method of analysis. Tests were conducted on props at 7-, 9- and 11-foot heights, using the vertical only, biaxial, and eccentric loading profiles. The props under development were a non-yielding support with a design capacity of 50 tons. Each unit included a threaded spindle arrangement (see figure 4), to accommodate entry height variations of up to one-foot and to generate a preload to secure the prop against the mine roof during installation. The procedure utilized in the previous example was used to calculate the performance parameters and initial eccentricity that coincides with the measured peak loads for each of the test specimens.

Height Effects

The Parametric Column Analysis method was used to evaluate the performance of the new prop design at three different heights when subjected to a 3:1 vertical-to-horizontal displacement load profile. Since the props are non-yielding and very stiff, the yield load was achieved in about 0.3 inches of vertical convergence. This means that the horizontal motion applied to the prop was about 0.1 inches and was insignificant in this particular case. The results of the analysis are shown in table 1 (see Appendix).

The calculated stability parameters predicted that the spindle would fail first for the 7- and 9-ft props ($\Psi_{spindle}>\Psi_{prop}$) and the pipe section would fail first for the 11-ft prop ($\Psi_{prop}>\Psi_{spindle}$). The test results confirmed that the less stable component failed for these configurations. The values calculated for the initial eccentricity corresponding to the 7-, 9- and 11-ft props were 0.072, 0.085 and 0.089 inches, respectively. Using these eccentricity values, it is estimated that the failure load of the pipe section was 168 kips for the 7-ft prop and 152 kips for the 9-ft prop. Likewise, the failure load for the pipe in the 11-ft design was 111.8 kips, while the spindle failure load was estimated to be 115 kips with the same eccentricity. All of these specimens exceeded the 50-ton capacity design goal.

Boundary Condition Effects

Non-yielding props are typically installed using a header board or a yield dish at the roof interface to increase the amount of entry closure required to cause the prop to fail. In this case, an oak header board measuring 20 x 9.5 x 2 inches was used and the yield dish was a prototype made from steel that was approximately 18 inches in diameter. Figure 5 shows the laboratory test results to compare the performance of props with these different boundary conditions. An additional 0.7 inches of displacement was required to fail the prop with the header board and an additional 2.3 inches was required to buckle the prop with the dish header. Another benefit of the yield devices is to distribute the support load over a wider area of the roof.

A parametric column analysis for these initial boundary conditions was completed to determine the eccentricity. The results are shown in table 2. The props were identical and therefore the stability parameter was the same for all the specimens. Notice that the initial eccentricity increased from 0.073 inches for the full contact specimen to 0.099 inches for the oak header board and increased to 0.124 inches for the dish header. The result of this increase in eccentricity was that the capacity of the support with an oak header was reduced by 13.6 percent and by 23.6 percent for the dish header compared to the full contact condition provided by the 8x8-in flat steel head plate. The full contact prop and the prop using a header board exceeded the 50-ton capacity design requirement specified by the manufacturer. The prop using the prototype dish header failed at 96 kips (48 tons).

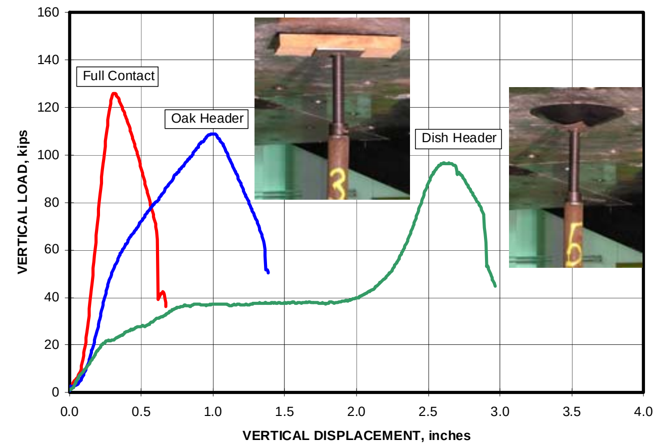

Figure 5. The effects of boundary conditions on prop performance.

Table 2. Impact of boundary condition on eccentricity.

Boundary Condition	Flat	Oak	Dish
Component Analyzed	Spindle	Spindle	Spindle
Prop Height, ft	7	7	7
Spindle Height, ft	1	1	1
PARAMETRIC COLUMN ANALYSIS			
Ψ - Stability Parameter	0.588	0.588	0.588
θ - Strength Parameter	0.550	0.475	0.420
η - Eccentricity Ratio	0.294	0.396	0.495
SUPPORT/COMPONENT FAILURE ASSESSMENT			
Component Failure	Spindle	Spindle	Spindle
Measured Prop Capacity, kips	126.1	108.9	96.3
REQUIRED ECCENTRICITY TO PRODUCE MEASURED SUPPORT CAPACITY			
Initial Eccentricity, in	0.073	0.099	0.124

Eccentric Loading Analysis

An analysis comparing the performance of two 11-ft props was completed to evaluate the affect of a severe eccentric load application due to a single wood wedge between the prop and the roof (figure 6). The material and geometric parameters for the props were identical to the previous examples, so the stability parameter for the whole prop (Ψ_{prop} = 0.807) and for the spindle section ($\Psi_{spindle}$ = 0.588) as shown in table 3, remained the same as used in previous analyses.

Table 3. Impact of wedging or eccentricity.

Support Configuration	Flat End Plate		Wedged End Plate	
Prop/Component	Prop	Spindle	Prop	Spindle
Height, ft	11	1	11	1
Boundary Condition	Flat	Flat	Wedged	Wedged
PARAMETRIC COLUMN ANALYSIS				
Ψ - Stability Parameter	0.807	0.588	0.807	0.588
θ - Strength Parameter	0.588	0.510	0.419	0.345
η - Eccentricity Ratio	0.111	0.344	0.220	0.680
SUPPORT/COMPONENT FAILURE ASSESSMENT				
Measured Prop Capacity, kips	113.4		79.2	
Component Failure	Pipe		Spindle	
REQUIRED ECCENTRICITY TO PRODUCE MEASURED SUPPORT CAPACITY				
Initial Eccentricity, in	0.086		0.170	

Figure 6. Wedged prop for eccentric loading.

The prop with uniform steel plate contact buckled in the pipe section with a calculated eccentricity of 0.086 inches. The wedge at the roof contact for the second support configuration created an initial eccentricity value of 0.170 inches. Figure 7 shows the effect of increased eccentricity on the computed failure load of the two prop components. If the eccentricity exceeds 0.113 inches, the prop will fail to meet the design load capacity, and if the eccentricity exceeds 0.130 inches, the spindle will fail at a lower load than the pipe. The effect of the severe eccentric load on the performance of the prop was a 30 percent reduction in support capacity compared to the full contact test and buckling failure of the spindle rather than the pipe.

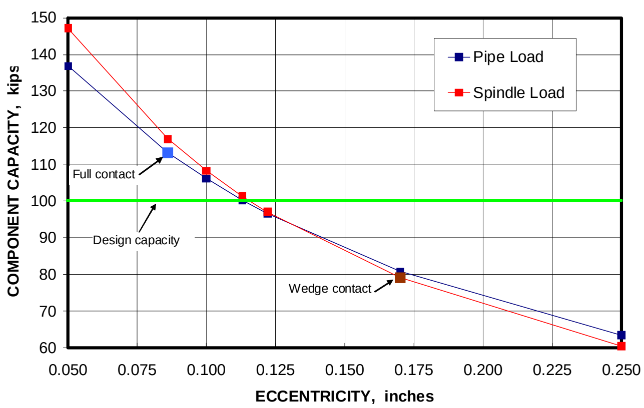

Figure 7. Effect of eccentricity on 11-ft prop.

Application of Parametric Column Analysis to Estimate Prop Capacity

The range of values for the initial eccentricity calculated from the laboratory test results in the previous section can now be used for estimating prop capacity. The initial eccentricity ranged from 0.072 to 0.089 inches for uniform contact conditions of props ranging in height 7 to 11 feet. The initial eccentricity for props with a header board at the roof interface was 0.099 inches and 0.124 inches with an 18-in-diameter steel dish at the roof contact. The application of biaxial displacements had minimal effect on the calculated eccentricity for non-yielding props. For the 7-foot height, the eccentricity was 0.073 inches for vertical only loading and 0.072 inches for biaxial load application. For the 11-foot height, the eccentricity was 0.086 inches for vertical only loading and 0.089 inches for biaxial loading.

Based on this range of initial eccentricities calculated from the MRS testing results, a value of 0.075 inches will be used to evaluate the performance of a yieldable prop design that was tested with uniform contact, using both the vertical only and biaxial load application. First, the stability parameter is calculated for the yieldable prop using equation 3 and the eccentricity ratio is calculated using equation 5 for the assumed initial eccentricity of 0.075 inches. For these test specimens, the stability parameter was computed as 0.165 and the eccentricity ratio was 0.076. Using these values and equation 6, the strength ratio for the prop can be computed as 0.914. Multiplying the strength ratio by the material strength and the cross-sectional area of the prop gives an ultimate capacity of about 183 kips.

The performance curves from the laboratory tests for both the vertical only and the 3:1 biaxial loading and the capacity estimated from the parametric column analysis are shown in figure 8. Comparison of the ultimate capacity with the yield capacity of the prop indicates a factor of safety of 1.5 for the support load in this case.

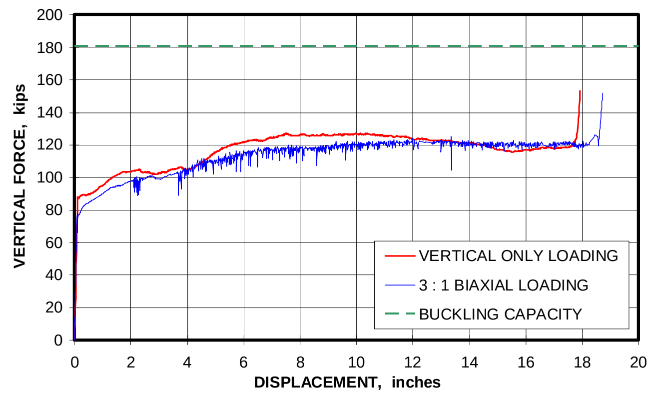

Figure 8. Estimated buckling load for a 50-ton yielding prop support.

The next goal is to calculate the maximum eccentricity that the yielding prop can withstand at the yield load. First the strength parameter (θ) is calculated by dividing the yield load by the prop area to determine the direct stress and then dividing by the material yield strength. The stability parameter is computed using equation 3. The eccentricity ratio can be computed from the strength and stability parameters using equation 7. Then using equation 8, the initial eccentricity can be calculated. From this analysis, the eccentricity required to buckle this yieldable prop would be 0.530 inches.

It is important to recognize that if the yield capacity of the prop is designed too close to the limit of instability, unexpected changes in eccentricity can cause premature buckling failure of yieldable supports. The prop support analyzed in this case has a capacity margin of about 60 kips between the yielding load and the buckling load, and the analysis shows that the design could withstand severe eccentricity. In addition, the biaxial test demonstrated successful performance under an even more severe load condition, where the base of the prop was displaced 6 inches horizontally relative to the top of the support during the test.

Key Points Derived From Parametric Column Analysis of Prop Supports

The Parametric Column Analysis methodology is a useful tool for analyzing the capacity reduction of prop supports due to eccentric loads and various boundary conditions. The values for the stability parameter and initial eccentricity that were obtained by the analysis of full-scale tests accurately reflected the observed strength performance of the supports. The findings listed here were particularly noteworthy and are important key points.

1. The stability parameter is a valid predictor of prop performance based completely on the physical parameters of the structure. This value can be used for a direct comparison of the stability of different prop designs. All props should be designed to provide a stability parameter less than 0.75. In this range, even with an eccentricity ratio of 0.2, the strength performance will be at least 50 percent of the material capability (see figure 3).

2. Laboratory test conditions for full, uniform contact at the ends of the prop produced initial eccentricity values that range from 0.072 inches at the 7-foot height to 0.086 inches at the 11-foot height. A header board increased the eccentricity to 0.099 for a 7-foot prop.

3. The relatively small horizontal displacement applied during biaxial loading was insignificant for the non-yielding props examined in this study. Additional research is needed to evaluate the impact of the biaxial load condition. During biaxial loading, the load axis is not offset from the central axis of the support as shown in figure 2, but rather rotates away from the central axis at the ends. Further analysis is needed to evaluate the effect of this condition compared to the offset loading assumed in the current analysis.

4. One laboratory test induced an extreme initial eccentricity of 0.170 inches, which caused a 30 percent decrease in the support capacity. This configuration, which only used a single wedge driven from one side, created a condition that can be easily avoided underground by driving wedges from both sides. Wedges should be used to fill voids as completely as possible, and should be installed to minimize eccentric contact.

5. Yieldable props should be designed with excess buckling capacity. If the yield capacity is too close to the buckling load, the props are susceptible to eccentric loads and premature failure.

Conclusions and Additional Research Recommendations

The options for replacement of bulky, crib-type secondary standing supports have been expanded by the development of new prop support designs in recent years. Although cribs can meet the need for support, there are many disadvantages to their use. The volume of material that must be transported underground, the labor required for installation, and the injuries associated with material handling and construction to name a few. Prop supports, that can match the capacity of cribs have been developed, and these supports can reduce the material handling requirements and the associated installation injuries. It is critical that any new support system introduced has the strength, stiffness and stability demanded by the application.

The Parametric Column Analysis methodology is an effective tool for the evaluation of props. It provides direct measurements of structural stability and the impact of eccentric loading on strength performance. These measurements allow the direct comparison of the stability of different prop designs and reinforce the importance of installation practices that minimize eccentric loading. The strength parameter from the analysis can be used to calculate a factor of safety for support design. In order to facilitate this design approach, eccentricity values for support loading must be established. The values calculated for the initial eccentricity from the laboratory tests thus far are limited to one non-yielding support. Additional tests must be conducted on other prop designs to determine if the eccentricity values are consistent or vary by design.

More testing is also required to develop complete installation guidelines. However, the installation should always minimize eccentricity to preserve capacity. Using Parametric Column Analysis to evaluate a yielding prop also showed the effectiveness of designing the yield load capacity well below the ultimate buckling capacity to enable the prop to withstand severe eccentric loading.

New testing protocols for props should be developed to induce bending moments at the ends of the props to simulate roof sag or floor heave. This test configuration will also be used to analyze the effect of the opposing moments created by horizontal displacement and inclined installation of the prop. An outcome from this continued research will be to determine if and when a spherical or pinned end condition is beneficial because of the reduction of bending moments.

The advantages of using prop supports to reduce material handling injuries will only be realized if the supports meet the requirements for ground control. The determination of the engineering limitations of props is crucial to ensure that the supports have the capabilities to meet or exceed the demands of the application.

References

Barczak, T.M. (2000), "NIOSH Safety Performance Testing Protocols for Standing Roof Supports and Longwall Shields," In the *Proceedings: New Technology for Coal Mine Roof Support,* Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000-151, IC 9453, pp. 207-221.

Timoshenko, S. and G.H. MacCullogh, (1949), *Elements of Strength of Materials, Third Edition*, D. Van Nostrand Co. Inc., New York, pp. 291-292

Dishongh, BE (2002). Universal Column Formula. In: ASCE Practice Periodical on Structural Design and Construction, Vol 7 No 3, August 1, 2002. pp 118-121.

Wright, Douglas (1999), "Notes on Design and Analysis of Machine Elements," http://www.mech.uwa.edu.au/DANotes/buckling/columns/columns.html DANotes: Buckling – Practical Columns; Updated 2005. Department of Mechanical and Materials Engineering, the University of Western Australia.

Appendix

Table 1. Impact of height on eccentricity.

Design Parameter	**7 ft Prop**		**9 ft Prop**		**11 ft Prop**	
	Full Prop	**Spindle**	**Full Prop**	**Spindle**	**Full Prop**	**Spindle**
Height, ft	7	1	9	1	11	1
Outer diameter, in	3.563	2.00	3.563	2.00	3.563	2.00
Wall thickness, in	0.254	1.00	0.254	1.00	0.254	1.00
Material strength, ksi	73	73	73	73	73	73
Component length, in	84	12	108	12	132	12
K – end factor	0.5	2.0	0.5	2.0	0.5	2.0
Effective length, in	42	24	54	24	66	24
Area, sq in	2.64	3.142	2.64	3.142	2.64	3.142
Moment of inertia, in^4	3.634	0.785	3.634	0.785	3.634	0.785
Radius of gyration, in	1.173	0.500	1.173	0.500	1.173	0.500
Slenderness ratio	35.80	48.00	46.03	48.00	56.29	48.00
Critical buckling stress, ksi	223.3	124.2	135.1	124.2	90.4	124.2
SUPPORT/COMPONENT FAILURE ASSESSMENT						
Component failure	Spindle		Spindle		Pipe	
Measured support capacity, kips	127.4		117.4		111.8	
PARAMETRIC COLUMN ANALYSIS						
ψ - Stability parameter	0.327	0.588	0.540	0.588	0.807	0.588
θ - Strength parameter	0.870	0.555	0.786	0.512	0.580	0.502
η - Eccentricity ratio	0.093	0.287	0.110	0.342	0.115	0.356
REQUIRED ECCENTRICITY TO PRODUCE MEASURED SUPPORT CAPACITY						
Initial eccentricity, in	0.072		0.085		0.089	