NUMERICAL MODELING FOR INCREASED UNDERSTANDING OF THE BEHAVIOR AND PERFORMANCE OF COAL MINE STOPPINGS

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ABSTRACT

In underground coal mines, concrete block stoppings are widely used to control mine ventilation. Although stoppings are not intended as roof support, they are subjected to roof to floor convergence, and may fail as a result of this loading. Premature failure of stoppings can significantly affect mine ventilation, limiting the amount of fresh air reaching the working faces and increasing the risk for methane explosions. Softening materials are often used in stoppings to reduce the damaging effects of roof to floor convergence. However, to date, research has not focused on the behavior of stopping construction materials subjected to roof or floor loading, leaving the design process to trial and error.

A combination of numerical simulations and large scale physical tests were employed to develop a scientific understanding of stopping performance. The first series of physical models were constructed using standard CMU (concrete masonry unit) blocks and tested in a load frame. The behavior of these walls was simulated with a distinct element model. A key finding was that very small variations in block size and irregularities in block shape significantly affect wall performance. These variations, which are inherent to the type of blocks typically used underground, create stress concentrations that initiate the failure of stopping walls. A second series of models employed concrete stoppings that incorporated wood planks, a shredded wood material, and foam planks like those commonly used underground. Numerical models were again able to match the physical test data. Analysis of the softening layers used in stopping construction indicated that the strength and stiffness of the material relative to that of the wall is crucial in determining the amount of roof to floor convergence the wall can withstand prior to failure.

The product of this study is a numerical model that can be used to evaluate the performance of stopping materials and different wall geometries in a controlled environment. Testing was done in a laboratory setting with walls constructed on flat, parallel surfaces and subjected to uniform loading at a constant rate. Parametric studies with the model indicate that in this ideal environment it is possible to control the amount of vertical displacement the stopping can withstand by adjusting the number of softening layers built into the wall and the thickness of the layers. Additionally, under these conditions, the position of softening layers within the wall appears to have little effect on the amount of displacement walls can withstand prior to failure.

INTRODUCTION

Ventilation stoppings, often made of dry-stacked concrete blocks, are crucial to maintaining safe, clean air courses in underground coal mines. Stoppings are not designed as roof support, but are often subjected to vertical loading and may fail when roof to floor convergence occurs. Failure of stoppings significantly disrupts the mine's ventilation system and can lead to a number of problems, including contaminated air at the working faces and increased risk of fire or explosion. In order to increase the amount of roof to floor convergence a concrete block stopping can withstand prior to failure, softening materials, such as wood or foam, can be incorporated into the design of the stopping. However, very little research has been done to examine the effects of roof to floor convergence on stopping behavior and design of these alternative stoppings often consists of trial and error. A notable exception is the investigation by Oyler et al., (2001) into the response of stoppings subjected to vertical loading from roof movements, which concluded that stoppings are able to resist a significant amount of roof loading. The study also raised the question of softening layers and to what extent a stopping should be designed to yield as a means of lengthening its useful life.

The goals of this study were to better understand the behavior of concrete block walls, evaluate the relative effects of incorporating a variety of softening materials into a concrete block wall, and to use a numerical model to develop some principles of stopping behavior that can serve as guidelines for stopping design. In order to achieve these goals, numerical modeling was done in conjunction with physical testing in the Mine Roof Simulator (MRS) at the Pittsburgh Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH). Because of its large platen size and high load capacity, the MRS provided a unique opportunity to study the complex problem of stopping failure in a controlled environment.

Development of a numerical model capable of accurately simulating the behavior of a concrete block wall began with a study into the mechanism by which stopping failure occurs. A combination of physical tests and numerical modeling revealed a complex failure mechanism. A set of realistic material properties for the model were established through a process of literature search, physical testing, and numerical modeling of a single concrete block. A numerical model was generated in UDEC (Itasca, 1985) to simulate the behavior of walls with and without softening layers and the output was verified with physical data. Finally, the model was used to evaluate the behavior of softening materials and to determine three basic principles of stopping behavior that can be used in the design of stoppings to withstand vertical loading.

DRY-STACKED BLOCK STOPPING BEHAVIOR

Failure Mechanism

Five stopping wall sections with no softening layers were tested in the MRS to study the behavior of concrete block walls subjected to vertical loading. Each section was made of 21 blocks stacked in seven courses approximately 53 inches high, 48 inches wide, and 6.5 inches thick. The stopping dimensions were chosen with enough block interfaces to study the failure mechanism, but with a small enough number of blocks so that numerous physical tests could be performed and compared with numerical output. Two of the walls (noted in figure 1) were made of blocks that came from the same manufacturer and were fabricated on the same date. Each of the other three walls was constructed using blocks from different sources, but within each wall all blocks came from the same source. Figure 1 shows the stress-strain curves resulting from the five tests. Since all five walls were constructed using standard CMU blocks, which are intended to be equivalent in strength, the variability in the data is striking. The range of peak stress values is from approximately 550 psi to nearly double that at over 1,000 psi. The corresponding strain values range from 0.4 to 1.1%. Despite the variability in peak strength, the pre- and post-failure moduli are consistent at approximately 150,000 and 250,000 psi, respectively.

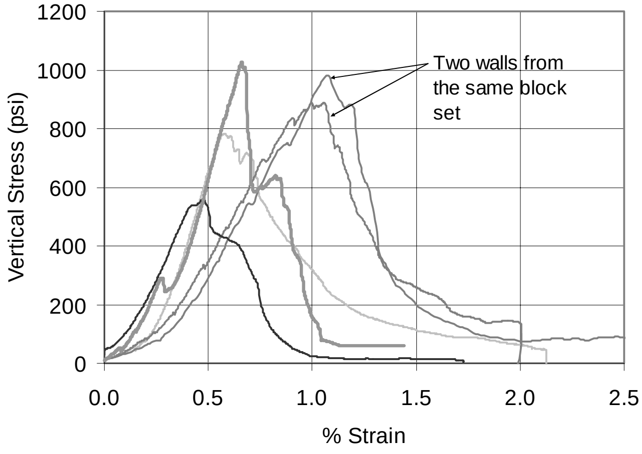

Figure 1. Stress-strain curves resulting from MRS testing of seven course standard CMU block walls dry-stacked with no softening layers.

In studying the behavior of these walls, it was determined that small variations in block size and shape have a key role in the failure of walls subjected to vertical loading (Burke, 2003). When adjacent blocks are not the same height, vertical loading results in a concentration of stresses in the blocks directly above or below the vertical interface, as shown in figure 2. These stress concentrations lead to the development of small cracks, which propagate through the concrete and into adjacent blocks, ultimately resulting in failure of the stopping. In the wall tests discussed above, this failure mechanism was observed and cracking occurred in multiple locations throughout each wall. Measurements of block height recorded prior to testing showed that variations in block size as small as 1/16 inch were contributing to this failure mechanism.

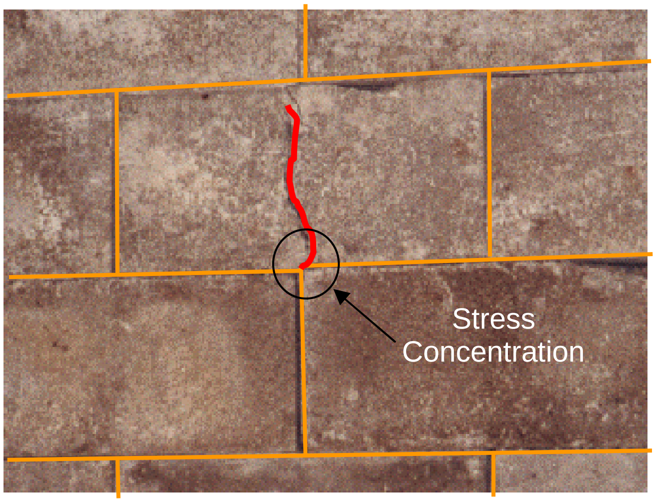

Figure 2. Difference in height of adjacent blocks causes stress concentration, which leads to the formation of tensile cracks in blocks above or below the block interface.

Table 1. Summary of results from property testing of fifteen individual standard CMU blocks

Block Set	Test #	Modulus (psi)	Peak Stress (psi)	% Strain at Peak
1	1	241,250	1,600	1.11
1	2	198,125	1,750	1.75
1	3	149,091	1,409	1.71
Set 1 Avg		**196,155**	**1,586**	**1.52**
Set 1 St Dev		**46,111**	**171**	**0.36**
2	4	262,742	2,968	1.91
2	5	262,742	2,871	1.96
2	6	197,778	3,255	2.3
Set 2 Avg		**241,087**	**3,031**	**2.06**
Set 2 St Dev		**37,507**	**200**	**0.21**
3	7	243,125	2,560	1.21
3	8	226,154	2,192	1.19
3	9	169,219	1,890	1.58
3	10	158,548	2,288	1.9
3	11	262,500	2,463	1.54
Set 3 Avg		**211,909**	**2,279**	**1.48**
Set 3 St Dev		**45,844**	**261**	**0.29**
4	12	213,830	2,234	2.22
4	13	160,122	2,138	1.81
4	14	251,200	2,125	2.18
4	15	219,091	2,384	2.78
Set 4 Avg		**211,061**	**2,220**	**2.25**
Set 4 St Dev		**37,763**	**120**	**0.40**
All Data Avg		**214,161**	**2,272**	**1.84**
All Data St Dev		**40,498**	**507**	**0.46**

Material Properties

In order to develop a realistic set of material properties, four sets of standard CMU blocks from different sources were tested in the MRS. Results of these tests are summarized in table 1. Although the weight and dimensions of all fifteen blocks were nominally the same, a substantial amount of variation in peak stress and strain exists within each block set and an even greater amount of variation exists between block sets. Among these fifteen samples, the peak stress varied from about 1,400 to 3,300 psi and the corresponding strain values varied from approximately 1.1 to 2.8 %. The amount of variation in modulus of elasticity between sets is similar to the amount of variation within each set and the average value of all data was selected as numerical model input. Unlike material tests meeting ASTM specifications, these tests were conducted on full scale samples and much of the variability may be due to dimensional differences rather than material properties, which should reflect the performance of blocks in the walls.

Material properties that could not be directly measured from physical data were obtained through literature search and FLAC (Itasca, 1986) modeling of a single block (Burke, 2003). The material properties used in the numerical model are shown in table 2.

Table 2. Material properties used in numerical simulation of wall behavior.

Property	Value	Units	Source
Density	10.82	lbs/ft^3	calculated from block measurements
Modulus of elasticity	214,161	psi	calculated from MRS data
Poissons ratio	0.2		American Concrete Institute 1986
Internal angle of friction	32	degrees	determined from numerical modeling
Cohesion	310	psi	determined from numerical modeling
Dilation angle	12	degrees	Vermeer and de Borst 1984
Tension limit	100	psi	Drysdale and Hamid 1984

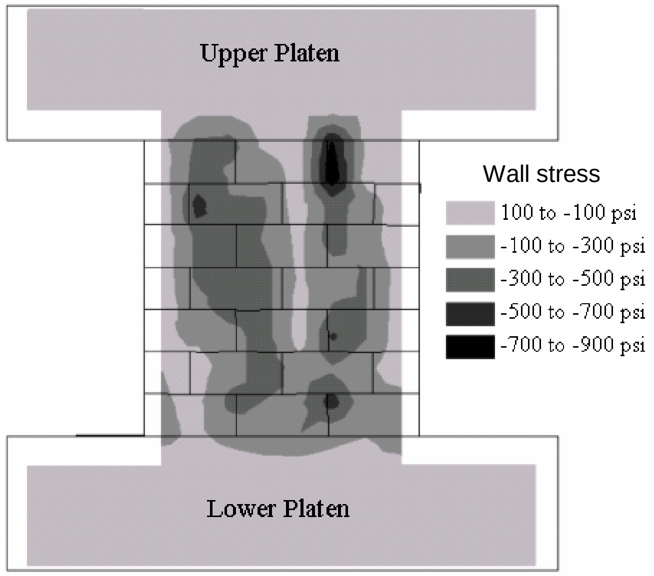

Figure 3. Non-uniform distribution of vertical stresses in the UDEC model of a seven-course concrete block wall dry-stacked with no softening layers.

Model Performance

A plane stress model was developed using the distinct element code, UDEC (Itasca, 1985). Based on the distribution of block sizes measured in the five physical wall tests, a set of non-uniformly sized blocks was randomly generated and the cell space mapping configuration (Hart, 1993) was used to define the blocks in the model. A strain-softening material model was used to simulate the behavior of the concrete.

A comparison between the numerical model failure mechanism and physical test data showed good correlation. Figure 3 shows the concentrations of vertical stress in the wall model. The vertical stresses are not distributed uniformly, but tend toward two distinct columns of high vertical stress. Additionally, two locations of particularly high stress, the dark areas in the top two courses of blocks, correspond to the interfaces with the largest height difference between adjacent blocks. These stress concentrations help confirm that the failure mechanism in the model is similar to that observed in physical data. Failure of the model occurred at a peak stress of approximately 900 psi (figure 4), which is similar to the results of the physical wall tests originally shown in figure 1 and included in figure 4 for comparison.

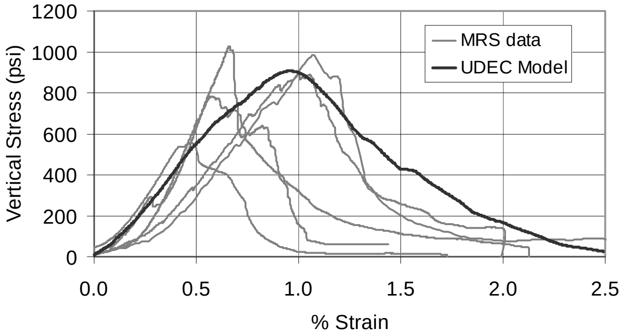

Figure 4. Comparison of stress-strain curves resulting from physical testing (MRS) and numerical modeling (UDEC) of a seven-course concrete block wall dry-stacked with no softening layer.

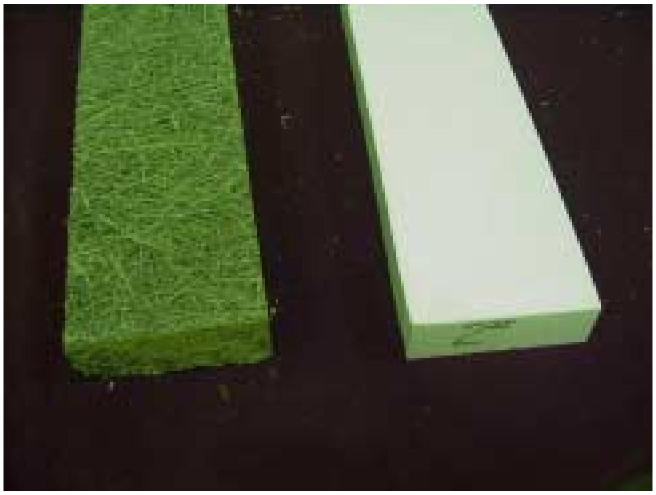

Figure 5. Fibroplank and foam materials used in MRS tests of block walls incorporating softening materials.

SOFTENING MATERIALS

Physical Testing

Four softening materials were tested under vertical loading: 1.5-inch-thick timber (poplar and pine) planks, Fibroplank, and a foam plank. Fibroplank is a 2.5-inch-thick shredded wood and cement product used by some mines as a softening layer in stoppings and shown in figure 5. A foam with a density of two pounds per cubic foot and a thickness of two inches was chosen for the study. The foam plank, also shown in figure 5, had a strength of 25 to 33 psi, according to the manufacturer. All four materials exhibited strain-hardening behavior and the results from the material testing are described in table 3. Of particular importance is the significant difference in strength between the pine samples. The two samples came from different sources, were not the same quality, and had not been subjected to the same drying processes. The stronger sample yielded at a peak strength more than double that of the weaker sample.

Table 3. Summary of results from property testing of four softening material specimens.

Material	Thickness, (in)	Sample number	Yield		Stress (psi) at:		
			Stress (psi)	% Strain	40% Strain	55% Strain	62% Strain
Poplar timber	1.5	1	900	8.5	1,555	2,380	--
		2	900	8.5	1,700	2,715	--
Pine timber	1.5	1	1,100	5.0	760	1,080	--
		2	500	8.0	1,555	2,370	3,510
Fibro-plank	2.5	1	200	6.0	690	--	--
		2	200	5.0	785	2,170	--
Foam	2.0	1	0	0.0	42	230	1,400

Walls were constructed and tested in the MRS to study the impacts on wall behavior of the four softening materials. In each case a single softening layer was placed below the top course of blocks, as shown in figure 6. The stress-strain curves resulting from these tests are given in figure 7.

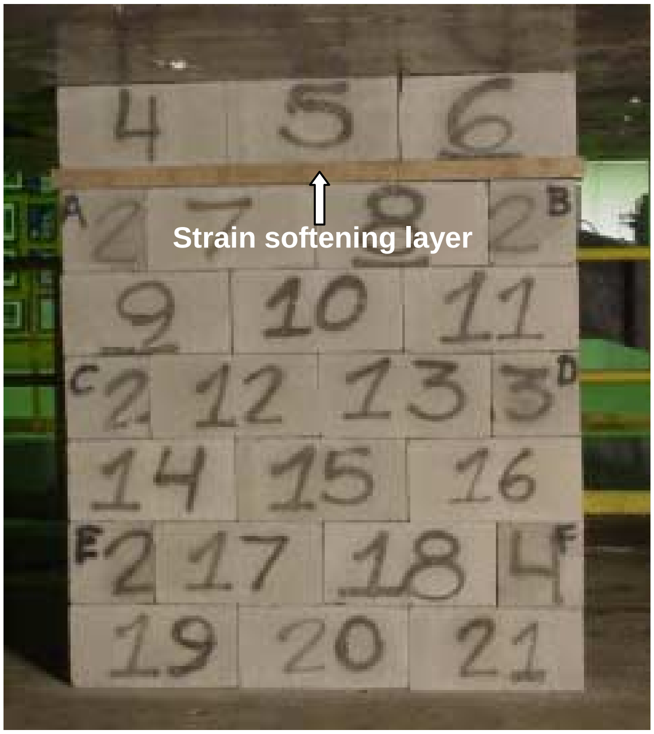

Figure 6. Seven-course concrete block wall dry-stacked with one layer of wood below the top row of blocks and tested in the MRS.

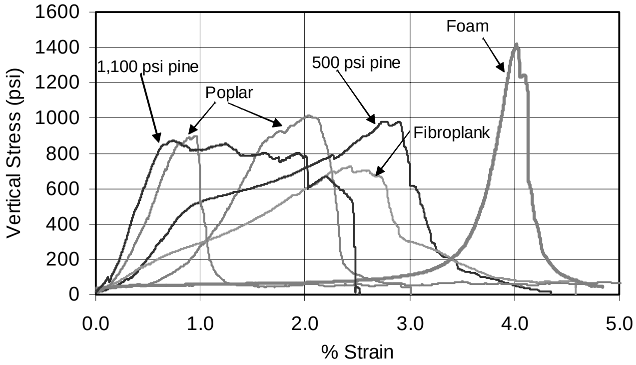

Figure 7. Stress-strain curves resulting from MRS tests of seven-course block walls built with one softening layer below the top course of blocks.

Of the two walls tested with poplar planks, one wall failed at a peak stress of 900 psi and the other around 1,000 psi. In the softening material tests, the poplar samples yielded around 900 psi. In figure 7, the effect of these wood layers can be seen in the stiffness change in the stronger wall between 900 psi and 1,000 psi when the wall failed. In the weaker wall, the effects of the wood are not as prominent because the blocks failed at the point where the wood was just beginning to yield (around 900 psi). The relatively large difference in strain is thought to be due to the initial contact configuration of the wall. The higher strain exhibited a very soft initial response which may be caused by the uneven block coated with the load frame and of the block-timber interface.

Similar results were seen in the walls containing the two types of pine discussed previously. As in the poplar wall tests, one wall failed around 900 psi while the other failed at approximately 1,000 psi. In this case, the wall containing the 500 psi pine layer clearly shows a substantial change in stiffness at 500 psi as the wood begins to yield. The other wall, however, was built using the 1,100 psi pine and the wall failed at 900 psi. Since the yield strength of the wood was higher than that of the wall, the effects of the wood on the wall behavior were minimal up to the peak stress of the wall.

The stress-strain curve from the wall containing Fibroplank follows the same trend as that of the walls containing wood. Although the change in stiffness is less dramatic in the Fibroplank wall, there is a small change around 200 psi, where the Fibroplank began to yield. Similar to the wood and Fibroplank, the foam was effective in softening the wall and allowing additional convergence to occur prior to failure of the wall. The foam, however, had very little stiffness initially and began to yield as soon as vertical displacement occurred. Thus, the foam allowed a significant amount of deformation under a very small load.

In analyzing the effects of softening layers on wall performance, focus was largely on the elastic portion of the wall stress-strain curves, rather than the post-failure behavior of the walls. The reason for this lies in the requirements placed on a ventilation stopping. In contrast to a roof support structure, where it is desirable to load up quickly and maintain the high load as long as possible, a stopping is more likely to be successful if it can respond to ground movement with minimal load. For example, in the test of a wall containing the 1,100 psi pine (shown in figure 7), after the peak load was reached, the wood began to split apart, deforming only slightly and allowing the wall to maintain a high load over 1.5% strain. However, during the time when the load was being maintained, the concrete was crumbling to an extent that would have impaired its ability to function as a useful ventilation structure. In contrast, in the wall with a foam layer, the displacement occurred while the stopping was supporting a very low load and no significant damage was sustained as the foam deformed. The key to extending the life of a stopping, then, is to increase the displacement experienced by the wall prior to reaching its peak load.

Model Performance

Based on the material tests conducted in the MRS, model walls were developed that simulated inclusion of the softening materials without changing the previously defined model properties. Correlation between the numerical models and physical data was remarkably good. Stress-strain curves from the poplar timbers, pine timbers, and Fibroplank models are given in figures 8, 9 and 10, respectively.

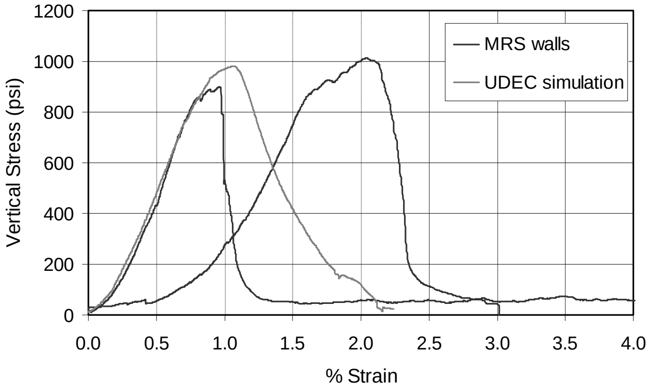

Figure 8. Comparison of stress-strain curves from physical (MRS) and numerical (UDEC) testing of a seven-course wall with one layer of poplar timber below the top row of blocks.

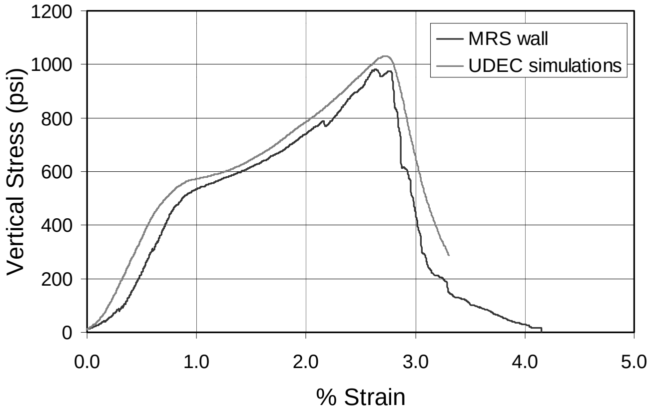

Figure 9. Comparison of stress-strain curves from physical (MRS) and numerical (UDEC) testing of a seven-course wall with one layer of 500 psi pine timber below the top row of blocks.

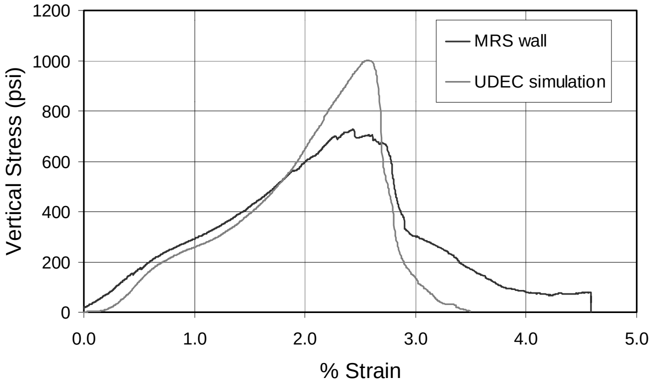

Figure 10. Comparison of stress-strain curves from physical (MRS) and numerical (UDEC) testing of a seven-course wall with one layer of Fibroplank below the top row of blocks.

Table 4. Summary of parametric studies conducted with UDEC model.

Timber layer description	Number of layers	Position(s) of timber layer(s)	Modulus of elasticity (psi) before yield	Wood yield point		Modulus of elasticity (psi) after yield	Peak stress (psi)	% Strain at peak stress	Displacement at peak stress, in
				Stress (psi)	% Strain				
2" Pine	1	below course 1 (top)	85,079	514	0.75	30,522	1,030	2.73	1.49
2" Pine	2	below courses 1 & 6	60,735	526	0.98	24,338	1,030	4.49	2.54
2" Pine	3	below courses 1, 5, 6	55,757	522	1.14	17,571	1,030	6.06	3.55
2" Pine	4	below courses 1, 2, 5, 6	43,175	530	1.37	10,886	1,030	7.66	4.63
2" Pine	1	below course 1 (top)	85,079	514	0.75	30,522	1,030	2.73	1.49
2" Pine	1	below course 2	75,539	451	0.70	31,583	1,020	2.69	1.47
2" Pine	1	below course 3	65,873	543	0.88	32,411	1,010	2.60	1.42
2" Pine	1	below course 4	72,182	467	0.71	31,983	1,000	2.82	1.54
2" Pine	1	below course 5	83,657	514	0.76	28,222	1,020	2.69	1.47
2" Pine	1	below course 6 (bottom)	77,333	513	0.73	24,000	992	2.71	1.48
2" Pine	1	below course 1 (top)	85,079	514	0.75	30,522	1,030	2.73	1.48
4" Pine	1	below course 1 (top)	64,204	525	1.13	18,626	1,060	4.70	2.66
6" Pine	1	below course 1 (top)	50,292	509	1.38	13,558	1,070	6.33	3.70

PARAMETRIC STUDIES

The wall model containing a layer of soft pine most closely replicated the physical data and was used as the basis for parametric studies examining the behavior of various stopping designs. Due to the large amount of variability in block and wall behavior, it is very difficult to conduct studies such as these with only physical data. The numerical model, however, can be used to evaluate the effects of various changes in wall geometry separate from the effects of block variability.

The first parametric study was conducted to consider the effects of adding more than one softening layer to a wall. All layers were identical and the layers appeared to have very little effect on one another. The model showed that each additional softening layer resulted in a slight decrease of the overall stiffness of the wall and an increase in displacement approximately one inch, but did not appear to have an effect on the peak stress the wall experienced prior to failure. These data are shown in table 4.

The second parametric study examined the impact on wall behavior of moving the softening layer to different locations within the wall. Each model had a single pine layer placed in one of six possible positions within the wall. The six models indicated that the location of the softening layer did not have a significant effect on the overall wall behavior. The small amount of variation in modulus of elasticity, peak stress, and strain shown in table 4 is likely due to local inconsistencies in block size and shape that may behave differently when they are placed adjacent to the softening layer.

The final parametric study considered the effects of increasing the thickness of a single softening layer. The results of this study, shown in table 4, indicated that the effects of increasing layer thickness are similar, although slightly greater in magnitude than the effects of incorporating multiple layers. Adding a second two inch layer (for a total of four inches of softening material) resulted in a 1.05-inch increase in displacement prior to failure and a 6,184 psi decrease in modulus of elasticity. Similarly, replacing a single two inch layer with a four inch layer resulted in a 1.17 inch increase in displacement prior to failure and an 11,896 psi decrease in modulus of elasticity.

SUMMARY AND CONCLUSIONS

The behavior of dry-stacked concrete block stoppings was studied through a combination of physical testing in the MRS and numerical modeling. This process led to a number of important conclusions.

- Very small differences in block size and shape have a dramatic effect on the behavior of a wall, significantly reducing the magnitude of vertical load the wall can withstand prior to failure.
- Softening layers made of a variety of materials, including wood, foam, and Fibroplank, can be used to lessen the damaging effects of vertical loading due to roof to floor convergence.
- In order to design a stopping that can effectively withstand a projected level of roof to floor convergence, it is important to consider the relative strength and stiffness of the blocks and softening layers and to take into account the variations in these material properties that will likely exist.

An important output of the study was a set of basic principles governing the behavior of stoppings with softening layers under the conditions specified in the model. Such principles should be taken into account in the design of stoppings that will be subjected to vertical loading. Through comparisons of numerical and physical data, the model was shown to be capable of accurately simulating the behavior of a block stopping with and without softening layers. Parametric studies (using pine timber as a softening material) led to the development of three principles of stopping behavior.

- If multiple layers of a pine timber material are used in the same wall, each layer will increase the deformation by approximately the same amount.
- Under the test conditions simulated, the location of the softening layer within the wall has very little effect on the amount of deformation the wall can withstand prior to failure.
- Doubling the thickness of a single softening layer will increase the deformation of the wall slightly more than incorporating two layers of the original thickness.

The model was developed to study a complex problem in a controlled environment and has been used to simulate the flat surfaces and uniform loading conditions that exist in the MRS. Mine conditions will differ to varying extents from those in the MRS and for this reason, future studies should include adapting the model to replicate key mine conditions, such as an uneven roof and floor and non-uniform loading across the width of the wall. Stopping construction techniques and dimensions vary as well and these factors should be taken into account to facilitate study of other and more complex stopping design scenarios. Of course, the engineering design process cannot neglect MSHA regulations regarding wall strength and fire resistance. In order to develop more comprehensive design guidelines, consideration must also be given to these factors.

In addition to the vertical loading simulated in these models and physical tests, stoppings are subjected to transverse loading due to air pressure. This additional direction of loading in combination with non-uniform vertical loading may produce an out-of-plane buckling failure in stoppings that is difficult to reproduce in a two-dimensional model. Studying this type of failure is important in the development of innovative stopping designs and should be an integral part of future studies into stopping behavior.

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