Impact of deformable materials and convergence on the transverse load capacity of mine ventilation stoppings

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ABSTRACT: Deformable materials are sometimes added to ventilation stopping constructions to prevent damage caused by convergence in coal mines. However, adding deformable materials can significantly reduce the capacity of a stopping to resist transverse loading. As part of its mining health and safety program, the National Institute for Occupational Safety and Health (NIOSH) has conducted research on the effect of various materials with different deformation properties on the transverse loading capability of a stopping wall. Based on a three-point hinge method of failure, a half-wall method of testing in the NIOSH Mine Roof Simulator was used to simulate full-scale wall behavior. This simulated the fracture initiation and eventual failure of the stoppings from transverse loading. The impact of the modulus of elasticity of various deformable materials was examined in this study. A polystyrene foam block with a low modulus of elasticity, which is commonly used as a deformable material, was shown to degrade the transverse load capacity of the stopping by as much 95%. Other materials with higher modulus of elasticity preserved more of the transverse load capacity of the stopping, but were not able to absorb as much convergence. This paper presents the results of a parametric study that quantifies the impact of various deformable materials in block stopping construction under transverse load conditions.

1 Introduction

Ventilation stoppings are airflow control devices, typically dry-stacked concrete block walls, erected between intake and return airways to direct ventilating air throughout the working sections of underground coal mines. The Code of Federal Regulations (CFR) requires ventilation stoppings to meet a certain minimum transverse load, but they often fail to meet these criteria due to convergence loading. Under the freestanding load conditions, 2 kPa (39 psf) is designated in the preamble to the CFR as the minimum required transverse load capacity. In order to prevent premature failure from convergence, deformable materials are incorporated into the stopping construction. Currently, the most commonly used material is an expanded polystyrene foam, formed into squeeze blocks or planks, that are sandwiched between one or more courses of a block stopping. Figure 1 shows a 1.2-m (4-ft) wide section of a stopping wall with a 5-cm (2-in) thick foam plank placed between the top two courses of block, showing the wall before and after failure during a laboratory test. Figure 2 compares the response of the wall for vertical loading. As seen in figure 2, the foam increases the displacement at which wall failure occurs, thereby increasing the capability of the wall to accommodate the roof-to-floor closure of the mine entry.

Although the foam is effective in enhancing the yield capability of the wall and extending the service life of the stopping in response to the closure of the mine opening, what does it do to the transverse load capacity of the stopping? Before addressing that question, it is important to understand how the transverse load capacity of a stopping is assessed. The current CFR evaluates transverse loading of stoppings under freestanding loading conditions in accordance with ASTM E-72 specifications (Barczak and Batchler, 2006). In this condition, the transverse load capacity for dry-stacked stopping constructions is primarily

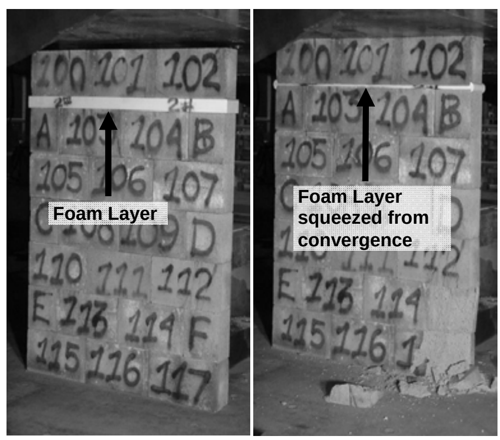


Figure 1. Two-inch-thick foam plank used to reduce the stiffness and extend the life of a block stopping by allowing the wall to absorb some deformation prior to failure. Only vertical loading is applied in this test.

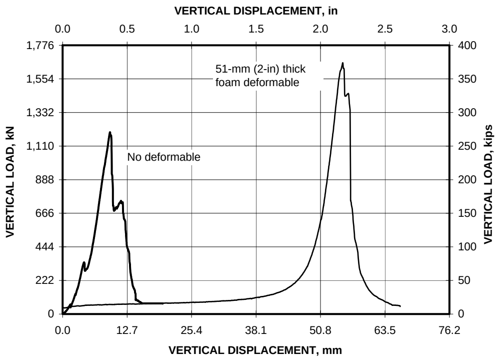


Figure 2. Comparison of a block stopping wall's response to vertical loading with and without a foam, deformable layer.

determined by the tensile strength of the sealant applied to the face of the stopping (see figure 3). Deformable materials are typically not included in these evaluations, but would not make much difference in this test protocol since the compressive forces developed within the freestanding wall are minimal and little damage would occur to them during the transverse load application. A new protocol has been developed that evaluates the transverse resistance of stoppings using equivalent arch loading conditions (Barczak and Batchler, 2006). The arch loading to approximate transverse loading is highly dependent upon the compressive forces developed within the wall as the wall arches between the mine roof and floor from the application of transverse pressure. In this condition, any deformable material in the wall can significantly degrade the transverse load capacity of the stopping. Using the protocol developed to simulate a three-hinge arch arrangement, the foam material decreased the

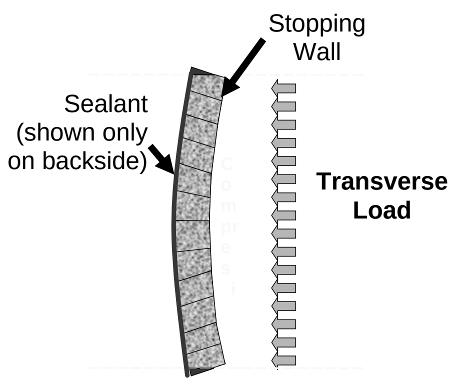


Figure 3. In freestanding evaluation, the sealant provides the main resistance to transverse loading.

transverse loading capacity of a representative stopping

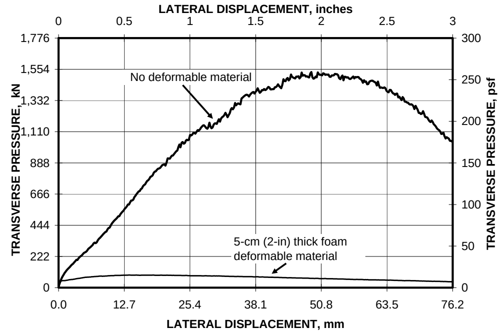


Figure 4. Under arch loading conditions, foam layer can severely degrade transverse load capacity of a stopping. This figure shows the results of the MRS transverse loading tests of a stopping with and without a foam layer.

made from solid concrete masonry block by 95% (24.4 to 1.3 kPa or 510 to 28 psf), as shown in figure 4.

This example clearly demonstrates that under arch loading conditions, which are believed to be representative of the loading conditions that occur in the mine (Barczak, 2005), the application of deformable materials to enhance the yield capability and survivability of the stopping due to convergence must be properly designed to preserve the transverse load capacity. The purpose of this paper is to determine the relationship between the modulus of elasticity of the deformable material and the transverse load capacity of the stopping under arch loading conditions.

2 Evaluation of Transverse Pressure under Arch Loading Conditions

Ventilation stoppings bridge the gap between the mine floor, roof, and pillars providing a restrained boundary condition. When a transverse pressure acts against the face of a stopping, the wall deflection is restrained by the mine roof and floor abutments creating a three-hinge arch. In order to simulate this arching mechanism, a half-wall section of a stopping is placed in the NIOSH's Mine Roof Simulator (MRS) (see figure 5). The half-wall is then hydraulically clamped to a fixed vertical height. The upper platen remains fixed in place as the lower platen moves horizontally, causing the wall to rotate. As the base of the wall is forced to move horizontally, hinge points and deformation zones are created at the ends of the wall on opposite sides, consistent with the arch loading mechanism. The horizontal force applied to the ends of the half-wall is measured and is equated to the transverse load acting on the wall (see figure 6) (Barczak, 2005).

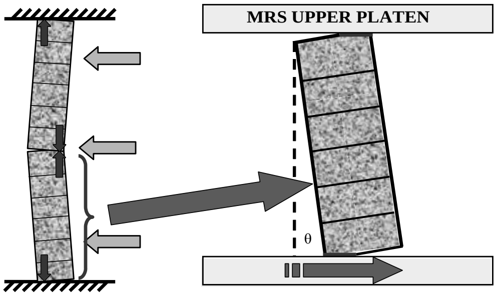
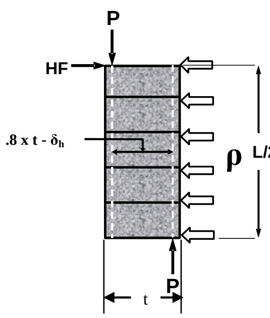


Figure 5. Simulating rigid arching in the NIOSH Mine Roof Simulator.



Moment Equilibrium

$$\frac{w \times \rho \times L^2}{8} = HF \times L/2$$

$$\rho = \frac{2 \times HF}{w \times (L/2)}$$

ρ = transverse load,
w = width of the wall,
L = height of the wall,
P = thrust force, and
HF = horizontal force.

Figure 6. Moment equilibrium equations for half-wall section of stopping subjected to transverse loading.

A relationship between horizontal displacement and transverse pressure can be developed from figure 6. In figure 6, the equivalent horizontal force is shown acting on ends of the wall while the resultant arching thrust is acting perpendicular to the horizontal force. As the wall rotation increases the lateral displacement will increase (see figure 7), decreasing the horizontal force as shown in equations 1 and 2.

$$P \times (0.8 \times t - \delta_h) = HF \times L/2 \quad (1)$$

$$\rho = \frac{2 \times P \times (0.8 \times t - \delta_h)}{w \times (L/2)^2} \quad (2)$$

Where P = thrust load,
t = thickness of the wall,
δ_h = lateral displacement of the wall at the mid span,
HF = horizontal force,
L/2 = half-wall height,
ρ = transverse load, and
w = width of wall.

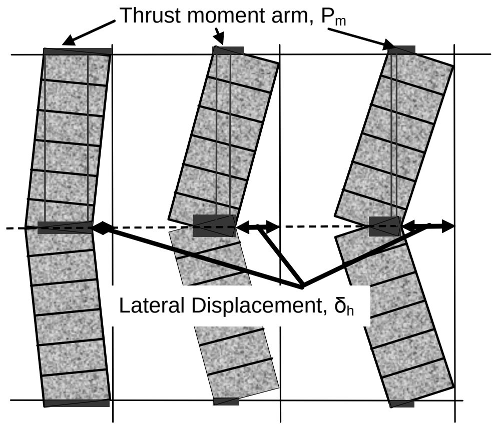


Figure 7. Diagram showing that increased lateral displacement of the stopping reduces the arch thrust which reduces the transverse load capacity of the stopping.

3 Half-wall Testing of Stoppings with Deformable Materials

A test program was designed to conduct a series of half-wall transverse load tests, using the protocol established to simulate arch loading, with a variety materials that provide a range of capability to prevent premature failure of the stopping due to convergence. The deformable material was placed at the top of a 1.2-m (48-in) high half-wall as shown in figure 8 to evaluate conditions that do not provide rigid arching behavior. This can be caused by either non-rigid roof or floor boundaries or by deformable material added to the wall construction for the purpose of absorbing ground deformation. A representative cellular concrete block with strength of about 3,450 kPa (500 psi) was used for the study. This is lightweight block with a material density of 618 kg/m^3 (38.6 lbs/ft^3) and a unit weight of 23.4 kg (51.5 lbs) for a 20x30x60-cm (8x12x24-inch) block.

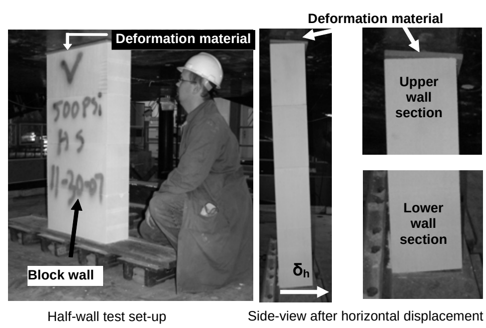


Figure 8. Deformable material placed at the roof interface in the MRS testing program.

Table 1. Material properties of the deformable materials.

Material	Thickness, mm (in)	Strain, %	Modulus, MPa (psi)	System Modulus, MPa (psi)
Low preload tests				
Plywood	12.0 (0.472)	14	34 (5,000)	287 (41,631)
Hard Rubber	9 3 (0.367)	14	18 (2,666)	276 (40,084)
Soft Rubber	9.8 (0.386)	12	4. (600)	195 (28,260)
Drywall	13.0 (0.513)	8	7 (1,000)	198 (28,752)
Homasote	13 1 (0.515)	17	15 (2,222)	241 (34,911)
Thick Foam	20.7 (0.815)	77	1 (130)	45 (6,475)
High preload tests				
Plywood	12.0 (0.472)	29	74 (10,800)	310 (45,000)
Hard Rubber	9 3 (0.367)	32	19 (2,750)	302 (43,781)
Soft Rubber	9.8 (0.386)	28	7 (1,000)	277 (40,224)
Drywall	13.0 (0.513)	24	8 (1,125)	229 (33,261)
Homasote	13 1 (0.515)	40	45 (6,500)	221 (30,647)
Thick Foam	20.7 (0.815)	99	14 (2,000)	276 (40,049)

The deformable materials were selected based on their modulus of elasticity to create a range of boundary conditions to study. These are not materials that are currently used in mine constructions. Table 1 documents the relevant properties of the test materials used in the study. The stress-strain response of some of these materials is nonlinear, many with strain-hardening behavior as they deform. For those materials, the modulus was approximated by taking the slope of the stress-strain response at the level of deformation which was consistent with the preload applied to the stopping prior to the application of transverse loading. The effective system modulus (E_{sys}) of the block wall and deformable material was computed using the series stiffness relationship described in equation 3 with the block wall modulus (E_w) of 310 MPa (45,000 psi) computed from testing of a unit block column. The preload is necessary to simulate the condition where convergence causes deformation of the deformable material prior to the application of transverse pressure. Two levels of preloading were evaluated: (1) a nominally small preload of about 345 kPa (50 psi) and (2) high preload of about 1,896 kPa (275 psi) equating to about 60 pct of the block strength.

$$k_{sys} = \frac{A_{sys} \times E_{sys}}{l_{sys}} = \frac{k_w \times k_{dm}}{k_w + k_{dm}} \qquad (3)$$

Where k_{sy} = system stiffness,
A_{sys} = surface area,
E_{sys} = system modulus of elasticity,
l_{sys} = system height,
k_w = wall stiffness, and
k_{dm} = deformation material stiffness.

4 Discussion of Test Results

Under arch loading conditions, the transverse load capacity of a stopping is determined by the force-couple formed by the thrust force at the hinge points generated by the deflection of the wall from the application of the transverse pressure against the face of the stopping. As the diagram in figure 7 illustrates, the thrust moment is reduced as the lateral displacement of the wall increases. Hence, all other things being equal, the transverse capacity of a stopping will decrease as the deflection of the wall increases.

The deflection is governed by the deformational properties of the wall and the surrounding roof and floor boundaries. Equation 2 provides a theoretical relationship between the wall deflection and transverse load developed by Barczak (2005). This is verified in the test data as shown in figure 9. Two conclusions are drawn from these results. First, the amount of lateral displacement decreases with increasing preload, thereby increasing the transverse pressure capacity of the stopping. Second, the slope of the curve increased for the high preload tests with the same deformable material applications that were used for the low preload tests.

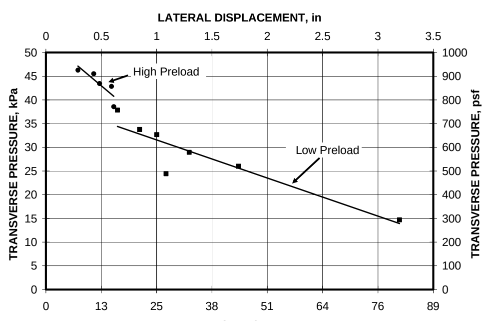


Figure 9. Transverse pressure capacity is reduced as the lateral displacement of the wall increases.

Barczak's analysis also indicated that the deflection would be governed by the effective material modulus or stiffness of the system (in this case, the block wall and surrounding roof and floor boundaries). Test data shown in figure 10 confirms this relationship. The modulus of the deformable material incorporated in the stopping ranged from a low of 1 MPa (130 psi) for a foam material to as high as 75 MPa (10,800 psi) for plywood. To put this in perspective, the block wall had an effective modulus of 310 MPa (45,000 psi). The lateral displacements increased from a low 12.5 mm (0.5 inches) to approximately 76.2 mm (3 inches) for the low preload tests and from 10.2 to 15 2 mm (0.4 to 0.6 inches) for the high preload tests. The slope of trendline for the high preload tests was about six times greater than the low preload test trendline. The reason for this is due in part to the strain-hardening of the material resulting in a higher system modulus at the higher preload.

Figure 11 shows the transverse pressure as a function

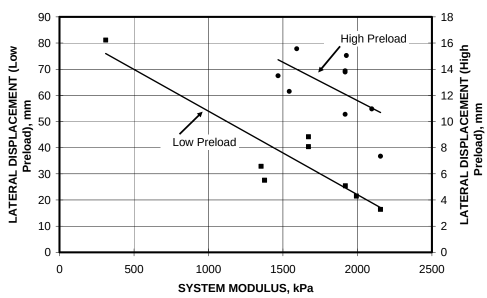


Figure 10. Lateral displacement decreases as the modulus of elasticity of the deformable material of the wall increases, causing an increase in system modulus.

of the system stiffness. The stiffness is related to the modulus by the relationship expressed in equation 3 and 4.

$$E_{sys} = \frac{E_w \times E_{dm} \times (L_w + L_{ss})}{L_w \times E_{dm} + L_{dm} \times E_w} \qquad (4)$$

Where E_{sys} = system modulus of elasticity,
E_w = wall modulus of elasticity, psi,
E_{dm} = deformable modulus of elasticity,
L_{sys} = wall height, and
L_{dm} = deformable height.

The chart shows that the transverse load capacity of a stopping (low preload situation) can be reduced by a factor of 2.5 (22 kPa or 450 psf in this case) by reducing the system stiffness by an order of magnitude through the addition of deformable materials to the wall construction. This reduction in transverse capacity could also be created by softening the roof or floor boundary condition compared to a rigid abutment situation. The impact of the deformable material can be mitigated by convergence that would induce a (vertical) preload on the wall. The slope of the low preload trendline is about twice that of the high preload tests shown in figure 11. The high preload tests conducted in this study found that the transverse load decreased by about 4.8 kPa (100 psf) for a 30 pct reduction in system stiffness.

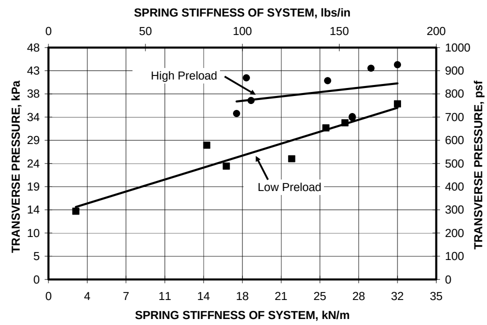


Figure 11. Transverse pressure capacity is increased as the system stiffness of the material of the wall increases due to the use of a higher modulus strain-softening material.

5 Conventional Portland Cement Block Studies

There has been increased interest in using cellular concrete materials for stopping construction due to their lower density material allowing lighter weight block fabrication or larger block sizes. Cellular block were used as the baseline for the study. However, stoppings have traditionally been constructed from solid concrete masonry style blocks (CMU's) made from conventional Portland cement and aggregate materials with a material density of 1,922 kg/m^3 (120 lbs/ft^3). These were also evaluated in this study using the same deformable materials that were used for the cellular block tests. Figure 12 compares the transverse load as a function of the system stiffness for the two block types. The results of the CMU blocks were different than expected and less consistent than the cellular concrete block:

- Lower system stiffness – The half-walls constructed from CMU block, which has a compressive strength of slightly more than twice that of the cellular block, had a lower stiffness and effective modulus. Normally, it would be expected that the stiffness would tend to increase with increasing compressive strength, but that did not happen in this case. It is believed that the reason for this apparent discrepancy is due to the poorer block dimensional quality control with the CMU block. These blocks did not stack together well since their thicknesses were not well controlled. This created stress concentrations over the contact loading surfaces that effectively degraded their loading capacity and resulting stiffness of the half-wall block column.

- Lateral displacement inconsistent with expected trend – As was shown in figure 9, an increase in lateral displacement should cause a decrease in transverse loading. There was little change in lateral displacement among the softer materials with the CMU tests, and the data indicate a weak trend showing increased displacement resulted in higher transverse load capacity. For this to happen, the arch thrust resultant locations must have been moved outward toward the block edges (see figure 6). While this is possible, additional testing will need to be conducted to confirm this hypothesis.

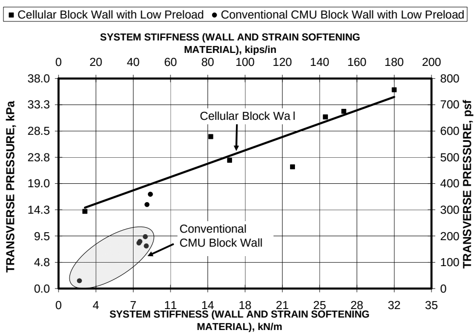


Figure 12. Performance comparison showing the transverse load capacity as a function of the system modulus between stopping walls constructed from cellular concrete blocks and Portland concrete blocks (CMU's).

6 Conclusions

Although ventilation stoppings have considerable load resistance, they often cannot fully control the ground movement and are still subject to the closure of the mine entry. Introducing a deformable material into the stopping construction reduces the stiffness of the ventilation stopping wall by lowering the effective system modulus. This helps to prevent premature failure due to the convergence, but will also degrade the transverse load capacity of the stopping under arch loading conditions. Using a weak foam material as is commonly done now, essentially removes the arch loading behavior of the stopping, and reduces the transverse load capacity back to a freestanding condition of 2 kPa (39 psf). This study shows that the transverse load capacity can be preserved by using a higher modulus material that is closer to that of the block. However, the compromise is that the higher modulus material reduces the capability of the stopping wall to absorb convergence without failing.

References

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