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Kyle A. Perry
Missouri University of Science and Technology, kperry@mst.edu

Rex A. Meyr

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KYLE A. PERRY*, REX A. MEYR*

EXPLOSION TESTING OF A POLYCARBONATE SAFE HAVEN WALL

BADANIE ŚCIANY OCHRONNEJ WYKONANEJ Z POLIWĘGLANÓW DLA STREFY BEZPIECZEŃSTWA W WARUNKACH WYBUCHU

The MINER Act of 2006 was enacted by MSHA following the major mining accidents and required every underground coal mine to install refuge areas to help prevent future fatalities of trapped miners in the event of a disaster where the miners cannot escape. A polycarbonate safe haven wall for use in underground coal mines as component of a complete system was designed and modeled using finite element modeling in ANSYS Explicit Dynamics to withstand the MSHA required 15 psi (103.4 kPa) blast loading spanning 200 milliseconds. The successful design was constructed at a uniform height in both half-width scale and quarter-width scale in the University of Kentucky Explosives Research Team's (UKERT) explosives driven shock tube for verification of the models. The constructed polycarbonate walls were tested multiple times to determine the walls resistance to pressures generated by an explosion. The results for each test were analyzed and averaged to create one pressure versus time waveform which was then imported into ANSYS Explicit Dynamics and modeled to compare results to that which was measured during testing for model validation. This paper summarizes the results.

Keywords: Mine safety, coal mining, explosion resistance, mining research

W następstwie poważnych wypadków w kopalniach, w roku 2006 MSHA uchwaliła Ustawę Górniczą na mocy której wszystkie kopalnie zobowiązane zostały do wyznaczenia odpowiednich stref bezpieczeństwa dla uniknięcia w przyszłości ofiar śmiertelnych wśród górników uwięzionych w kopalni w przypadku katastrofy uniemożliwiającej ucieczkę. Zaprojektowano ścianę ochronną wykonana z poliwęglanów zabezpieczającą strefę bezpieczeństwa w kopalniach podziemnych, jako element całego systemu zabezpieczeń. Ścianę zaprojektowano i modelowano w oparciu o metodę elementów skończonych z wykorzystaniem pakietu ANSYS Explicit Dynamics. Według wymogów MSHA ściana winna wytrzymywać ciśnienia 15 psi (103.4 kPa) w trakcie najsilniejszej fali wybuchu trwającej 200 milisekund. Odpowiedni projekt wykonano w odpowiedniej skali: połowie i ćwierci wysokości, jako obiekt jednolity. Modele zweryfikowane zostały przez badaczy z Uniwersytetu w Kentucky, z wykorzystaniem odpowiedniego tunelu testowego. Ściany wykonane z poliwęglanów zostały wielokrotnie przebadane aby określić ich wytrzymałość na ciśnienia powstające w trakcie wybuchu. Wyniki każdego z testów zostały przeanalizowane i uśrednione

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* MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY, USA

a otrzymany przebieg ciśnienia w funkcji czasu został zaimportowany do pakietu ANSYS Explicit Dynamics i zamodelowany, tym samym umożliwiając jego porównanie do wyników pomiarów wykonanych w ramach walidacji modelu. W niniejszej pracy zestawiono uzyskane wyniki prac.

Słowa kluczowe: bezpieczeństwo kopalni, górnictwo węgla, zabezpieczenie przed wybuchem, badania w dziedzinie górnictwa

1. Introduction

The use of safe havens in the mining industry has been in existence since the early 1900s when the U.S. Bureau of Mines first advocated their use to fight mine fires (Rice, 1912). Through the years, safe havens have evolved as technology and regulations advance to provide a life-sustaining environment for trapped miners unable to escape in the event of a mine explosion. Following the mine explosion accidents at Sago Mine, Alma No.1 Mine, and Darby No. 1 Mine in 2006, The Mine Improvement and New Emergency Response Act of 2006 (MINER Act) was established by the Mine Safety and Health Administration (MSHA) to improve safety, health, preparedness, and emergency response in US mines (CDC, 2009). The Mine Safety and Health Administration 30 CFR Parts 7 and 75, "Refuge Alternatives for Underground Coal Mines Final Rule", establish the MSHA requirements for refuge alternatives in underground coal mines (Department of Labor, 2008). The Final Rule also defines the purpose, scope, and design requirements for refuge alternatives. These design requirements were used for the development of the 15 psi (103.4 kPa) polycarbonate safe haven wall constructed and tested in this paper.

To achieve structural safety and blast resistance, the safe haven wall system was designed and modeled in ANSYS Explicit Dynamics to produce an adequate design capable of resisting a MSHA prescribed pressure versus time curve. The MSHA prescribed curve has a linear increase to 15 psi (103.4 kPa) at 100 milliseconds and then decreases linearly to zero at 200 milliseconds (Department of Labor, 2008). The designed system is a general single-degree-of-freedom design that is 20 feet (6.1 meters) long and 6 feet (1.8 meters) tall which covers a majority of the underground coal mines in Kentucky. By using single-degree-of-freedom analysis, the wall width can theoretically stretch to infinity. Therefore, the only dimension which affects the performance is the height. Once a successful wall was designed for a typical coal mine height, only minor modifications were necessary for taller or shorter walls. The supporting steel frame system is made up of Hollow Structural Sections held in place by C shapes, or steel channels, on the top and bottom of the system which are bolted to the roof and floor of the mine. All support system elements were structural steel with an ultimate strength of 60 ksi (413.7 MPa). The supports were spaced no closer than 30 inches (76.2 cm) per MSHA code for minimum support spacing as to allow a stretcher to be passed through the door panel (Department of Labor, 2008). The successful design consists of 14 hollow structural sections 8 × 4 × 0.625 inch (20.3 × 10.2 × 1.6 cm) vertical supports held in place by a C10 × 30 (C25.4 × 4.1) channel at the top and bottom. One inch (2.54 cm) thick polycarbonate panels with dimensions of 66 × 44 inch (167.6 × 111.8 cm) were placed on either end of the wall along with four 66 × 38 inch (167.6 × 96.5 cm) middle panels were bolted on the outside of the frame to complete the design. Further information on the design and modeling results can be found in Perry and Meyr (2013) and Perry and Lusk (2013).

2. Construction and Testing

The construction and testing of the polycarbonate safe haven wall design was performed at the University of Kentucky Explosives Research Team's (UKERT) high explosive shock tube facility in Georgetown, Kentucky. Construction and testing was performed for two different sized walls to analyze the design as best as possible within the dimension limitations of the shock tube. Reflected pressure measurements from either two or three sensors were collected at the blast-side surface of the wall at a 1 MHz sampling rate for each test. In addition to pressure measurements, deflection data of a specified point on the wall was taken at 20 MHz with a laser displacement gauge. The displacement location changed from test to test. These data were then used to import a pressure versus time waveform into the modeling software so direct comparisons could be made.

2.1. Half-Width Scale Polycarbonate Wall Construction

The UKERT shock tube has openings on each end to place structures for explosion testing. One end opening is approximately 2.44 meters by 2.44 meters (8 feet by 8 feet) while the other is approximately 3.05 meters by 3.05 meters (10 feet by 10 feet). The testing was to be performed on a 1.83 meter (six feet) tall wall, so modifications to the openings were necessary. A significant attempt was made to make the top-piece structure, which the top of the wall was attached to, as rigid as possible to simulate a mine roof. However, after testing, it was noticed that there was slight movement in the materials used to close off the parts of the opening which did not house the polycarbonate wall. Therefore, exact comparisons to the modeling cannot be made due to the assumption of fixed-end conditions in the models which does not allow the top of the wall to move at all; however, general trends are seen in the comparisons.

The construction process started with reducing the cross-sectional area of the existing 3.05 m by 3.05 m shock tube opening down to 1.83 m high by 289.6 cm (114 inches) wide to simulate a 1.8 m entry in a coal mine. The purpose of the reduction was to keep explosive pressures from easily escaping the areas around the wall. The width was chosen as it allowed for exactly three equally sized polycarbonate panels to be installed. The size reduction was achieved by placing eleven 8.9 × 30.5 × 304.8 cm (3.5 × 12 × 120 inch) oak boards on top of an I-beam support.

The I-beam was fastened horizontally through oak boards to the steel shock tube framing with bolts through angle pieces that also bolted to the web of the I-beam on both ends. The I-beam was also supported vertically by oak boards on each end. Once the I-beam and oak board size adjustment was in place, 1.6 cm (5/8 inch) threaded steel bars were inserted from the top of the shock tube frame down through holes previously drilled in the oak boards and I-beam to further anchor the cross-sectional size adjustment together.

With the shock tube opening to the required dimensions for the polycarbonate wall system, the steel frame was brought in to place and installed. Figure 1 shows the installed steel frame along with the oak board size adjustment and I-beam. As with the models, the sides of the wall system remained free to force a one way reaction.

Following the installation of the steel framing, 2.54 cm (one inch) polycarbonate panels were cut to the required 167.6 × 96.5 cm (66 × 38 inch) dimensions to fit the frame. After the polycarbonate was cut to the proper dimension, it was placed against the steel framing to mark the as-built holes in the steel framing system. The panels were then removed and holes were drilled where marked. The middle panel was marked first followed by the left and right side to ensure that any gaps between the polycarbonate were on the outside of the system. The completed polycarbonate wall installation can be seen in Figure 2.

Fig. 1. Half-Width Scale Steel Framing Installed in the Reduced Opening

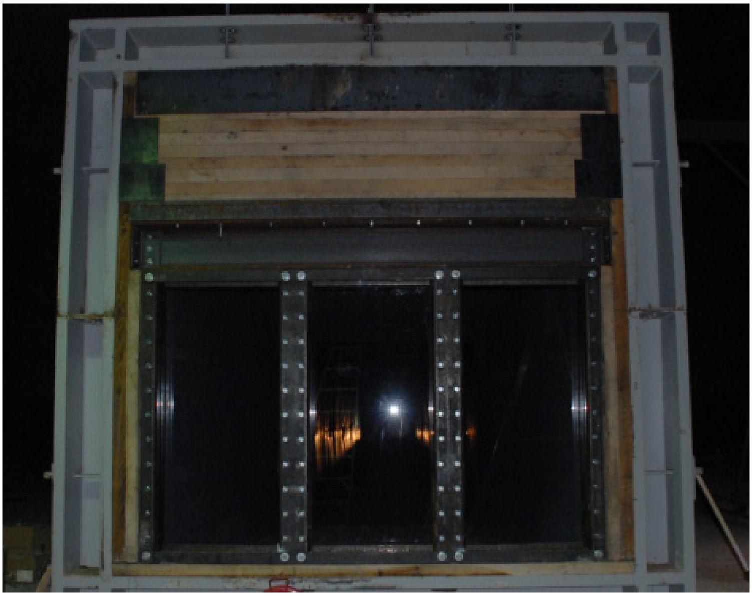

Fig. 2. Completed Half-Width Scale Polycarbonate Wall Installation

2.2. Half-Width Scale Polycarbonate Wall Explosion Testing Instrumentation

With the polycarbonate safe haven wall installed, the system was ready for explosion testing. The instrumentation setup consisted of three reflected pressure sensors located as shown in Figure 3 to record explosive pressures being experienced by the wall system and a displacement laser to record the deflections of the steel framing and polycarbonate panels. Four tests were performed to record deflections on the center polycarbonate panel, left-center vertical support (when looking at the wall from the side opposite of the explosion), far left half support, and the left polycarbonate panel. The deflections of the right side were assumed to be same as the left due to symmetry. The laser was moved for each test to record the deflections and the pressure sensors also recorded pressure for each test. Each test was also captured with standard and high speed video to document and identify any movement or significant action that occurs during the blast test. The pressure for each test was generated by a C4 charge 15.5 m (51 feet) from the wall. The use of a point charge has been shown previously to have a nearly planar impact on the test subject and that linear charges (detonating cord, gas explosions, etc.) have no signification effect on the waveform (Lusk et al., 2010). This half-width scale wall testing consisted of four tests.

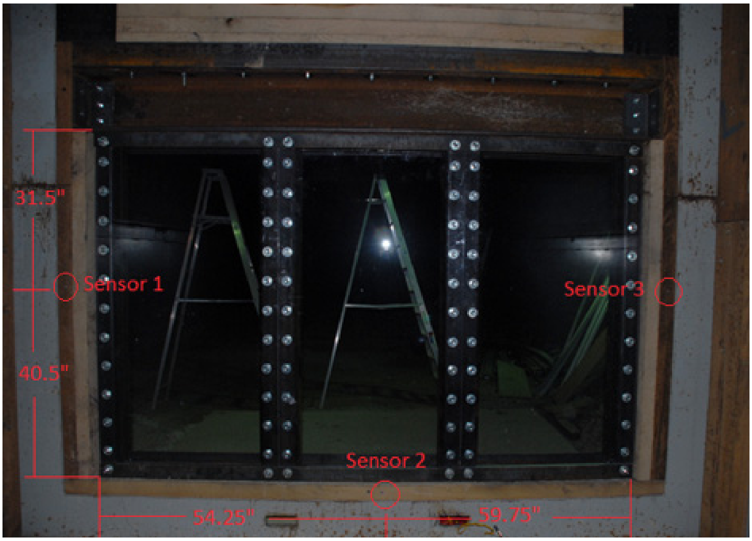

Fig. 3. Pressure Sensor Locations for Half-Width Scale Testing

2.3. Half-Width Scale Testing Results

The system faired very well against the blast pressures that it was subjected to in the tests. The pressures and impulses for each test and each sensor were recorded and then averaged to create one pressure versus time waveform for each test. Each averaged pressure waveform was imported into ANSYS Explicit Dynamics and AutoDYN and modeled against the system design to determine the deflection of each part that was measured during testing. The resulting deflections from the model and actual test can be seen in Table 1.

TABLE 1

Deflection Results from Models and Explosion Testing

Test Number	ANSYS Deflect. (cm)	Testing Deflect. (cm)	ANSYS Deflect. (in)	Testing Deflect. (in)	Average Pressure (kPa)	Average Pressure (psi)	Laser Location
1	3.099	2.305	1.220	0.907	52.469	7.610	Center of middle poly panel
2	0.847	1.862	0.334	0.733	52.400	7.600	Center of left-center steel support
3	1.289	2.303	0.508	0.907	53.021	7.690	Center of far left steel support
4	4.956	2.640	1.951	1.039	52.469	7.610	Center of left poly panel

The first item to take away from the table is that the required blast pressure was not met. Only approximately 52.4 kPa (7.6 psi) was reached while the requirement is 103.4 kPa (15 psi). Initial plans were to ramp up pressures over subsequent tests, but damage to the shock tube around the large opening was beginning. Therefore, a further reduction was necessary to meet the required pressures which is discussed later in this paper. However, models were still created and subjected to the measured pressure versus time curve so comparisons of the data could be made.

The deflection comparisons between the blast testing and the ANSYS models were performed using the deflection laser data and the displacements found by importing the pressure versus time waveform recorded during blast testing into ANSYS. The comparisons were performed for the four blast tests with each test measuring the deflection of a different component of the safe haven wall as show in Table 1. The deflections calculated from the model were greater on the polycarbonate panel and less on the vertical steel supports. The deflection comparisons can be seen in Figures 4-7.

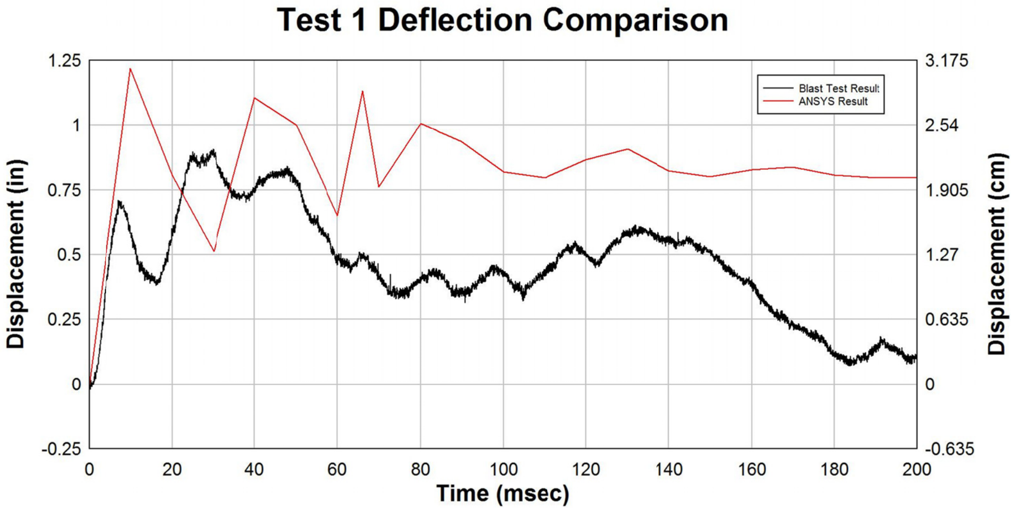

Fig. 4. Deflection at Center of the Middle Polycarbonate Panel

The curves comparing the deflection of the polycarbonate material in Figures 4 and 5 trend reasonably well with the predictions calculated by the model with a few exceptions. The ANSYS model calculates larger deflections, a longer wavelength (smaller frequency), and permanent displacements. This is most likely a result of the polycarbonate material used for the system being a relatively new material and does not have a material model within the software. A material model could not be created due the proprietary nature of the polycarbonate panels. Newer technology has allowed the Makrolon Hygard polycarbonate to be stiffer than the standard polycarbonate material model within ANSYS and deflections were expected to be smaller from testing than modeling. Perhaps the most interesting comparison between the models and testing is the fact that the model predicts plastic behavior. The displacement records from the testing show the panels coming back to near zero suggesting elastic behavior when accounting for small displacements in the overall testing structure and fixtures.

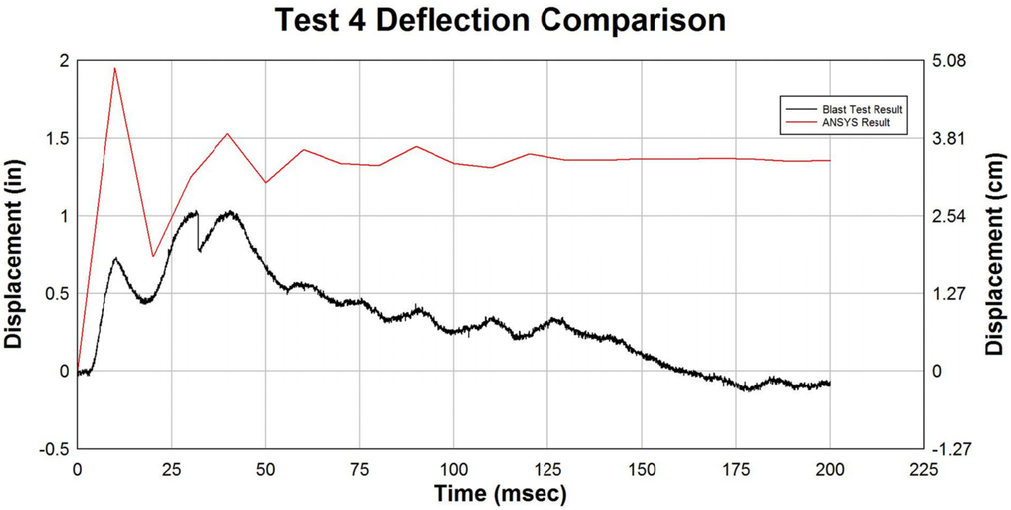

Fig. 5. Deflection at Center of the Left Side Polycarbonate Panel

The deflection comparison of the curves in Figure 6 and 7 are the result of blast testing on the steel frame component of the wall. These curves only show slight consistency with each other in displacement trend. This is most likely due to the steel frame of the wall being bolted to an I-beam, thus allowing for a pivoting action to occur during testing. Since the overall aperture of the shock tube was reduced, loading still occurred above the I-beam simulating a mine roof which would not be representative of an actual mine. The pivoting action allows the whole frame to move much more than if it was bolted to the roof of a mine. In turn, the deflection of the bolted steel structure is much more when compared to the fixed and bonded conditions of the frame in the ANSYS model. The steel frame deflection is also hindered by the fact that it was bolted together allowing for system to absorb more blast energy in multiple bolted connections compared to the fully bonded system used in ANSYS. However, it is again interesting the model predicting plastic behavior while the testing suggests elastic.

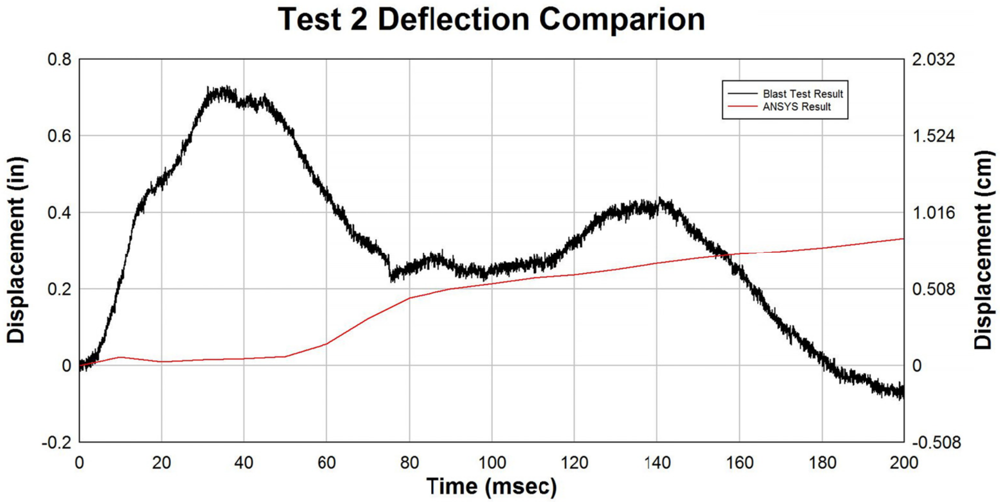

Fig. 6. Deflection Comparison of Left-Center Vertical Steel Member

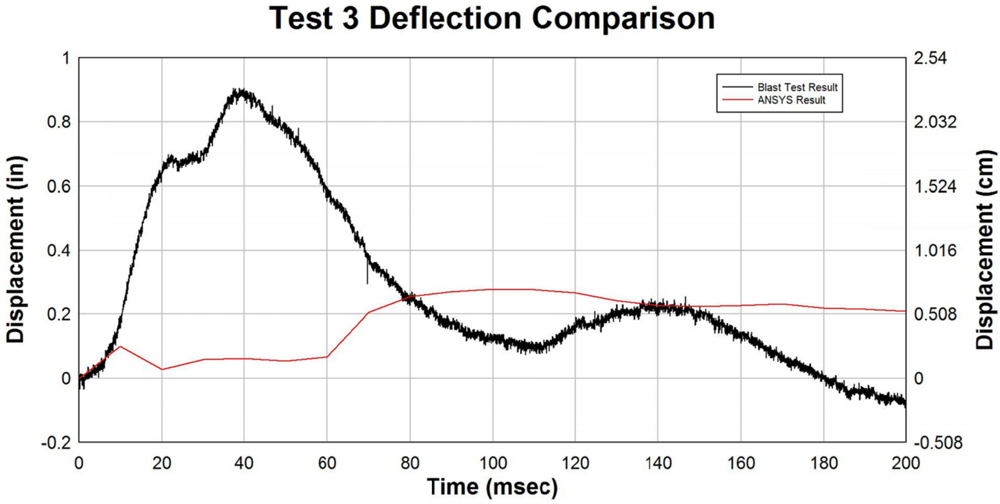

Fig. 7. Deflection Comparison of Far-Left Vertical Steel Member

The results show the required pressure for testing the design and MSHA approval was not met. Figure 8 shows the pressure curve comparison between the MSHA requirement pressure versus time curve and the max average testing pressure versus time curve. While reaching the peak pressure is not a problem within the shock tube, creating the prescribed waveform presents a difficult, perhaps impossible challenge. Several small scale tests of a new explosive material and detonation system were performed. While the pressures were lower than that of the C4 (approximately 27.6 kPa (4 psi), the waveform duration was longer and showed promising results.

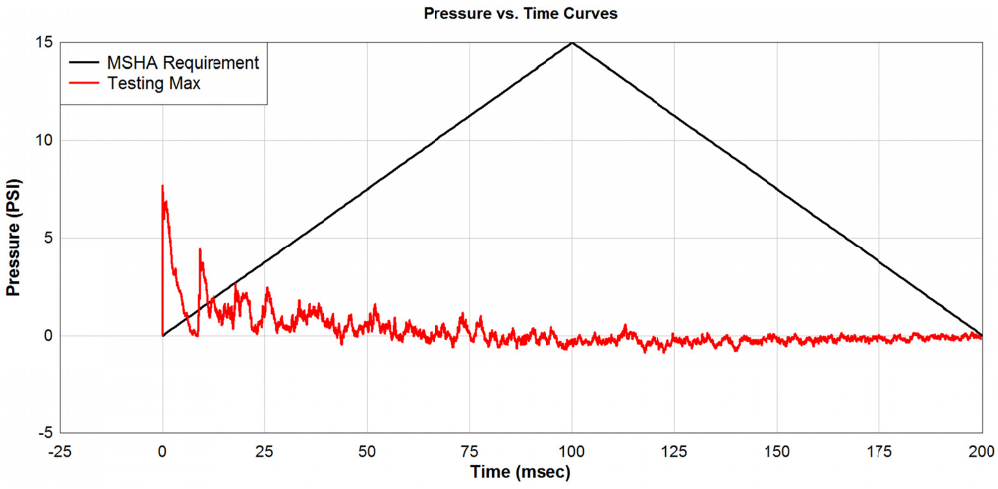

Fig. 8. MSHA Requirement Versus Half-Width Scale Measurements

However, damage to the shock tube did not allow for further investigation during this test series. Experiments to generate the MSHA prescribed waveform are currently being researched.

2.4. Quarter-Width Scale Polycarbonate Wall Construction

After the initial testing of the polycarbonate wall system, it was determined that additional testing needed to be performed to test the system at the MSHA prescribed 103.4 kPa (15 psi) pressure. To achieve this pressure without detrimental effects to the shock tube, a smaller polycarbonate wall system was constructed in the smaller opening of the shock tube. The test setup used a similar design in a 231.1 × 231.1 cm (91 × 91 inch) opening. The smaller design included the full design height of 1.83 m and used the whole 231.1 cm width. Also, one centered 167.6 × 96.2 cm (66 × 38 inch) polycarbonate panel was used along with two smaller 167.6 × 67.3 cm (66 × 26.5 inch) panels on either side. The vertical supports and polycarbonate panels from the first round of shock tube testing were able to be used again for this test; however, new channel had to be ordered and drilled to accommodate the reduced vertical support spacing on the ends. Due to the overall height of the vertical supports being for a 182.9 cm (72 inch) height, a similar size reduction method from the previous testing was used to reduce the overall opening. Two steel channel pieces were bolted on either end of the top frame channel to contain oak boards used for the size adjustment. The two channel pieces were also bolted to the surrounding shock tube frame through pieces of angle that were welded into the web of the channel. Once all the steel framing and oak boards were in place, the polycarbonate wall system frame was fastened to the framing of the shock tube to simulate it being bolted to the floor and roof of a mine. Roof bolts with a 2.54 cm diameter (1 inch) were installed on top to lock the oak boards and steel frame together; grade 5 1.27 cm (0.5 inch) bolts were used to secure the bottom channel of the wall system frame to the floor of the shock tube frame. Lastly, the polycarbonate panels were cut to size, drilled, and installed to finish the reduced system construction. The completed construction can be seen in Figure 9.

Fig. 9. Quarter-Width Scale Polycarbonate Wall System

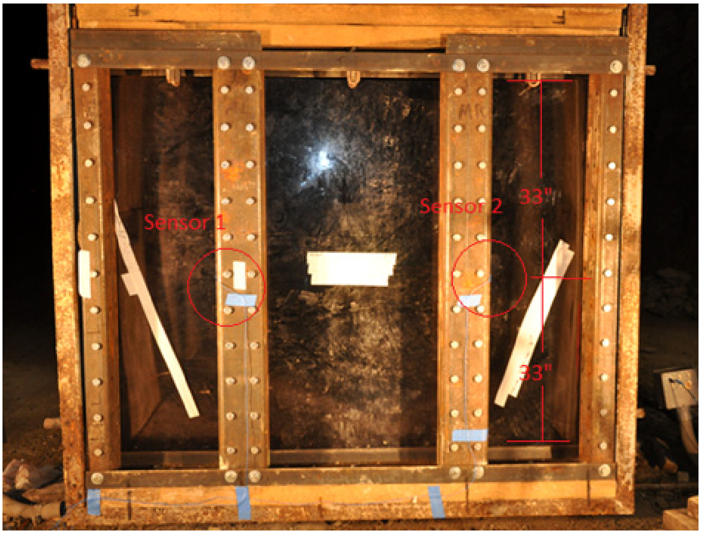

Fig. 10. Sensor Placement for Quarter-Width Scale Testing

2.5. Quarter-Width Scale Polycarbonate Wall Testing Instrumentation

The quarter-width scale testing also used pressure sensors to measure the explosion pressure experienced by the wall and a displacements laser to measure the displacement of the steel framing and polycarbonate panels. The testing setup for the additional testing consisted of embedding two pressure sensors in the polycarbonate just outside each center vertical support half way up each panel as shown in Figure 10. The laser was located in the same place for all tests and measured the deflection of the center polycarbonate panel. Each test was also captured with standard and high speed video to document and identify any movement or significant action that occurs during the blast test. The pressure for each test was created by hanging a C4 charge either 13.7 or 9.1 m (45 or 30 feet) from the wall. The quarter-width scale testing of the polycarbonate wall consisted of five tests.

2.6. Quarter-Width Scale Polycarbonate Wall Testing Results

The reduced width polycarbonate safe haven wall system also faired very well against the blast pressure applied during testing. The pressures and deflections were all recorded and can be seen in Table 2.

TABLE 2

Testing Results from Quarter-Width Scale Polycarbonate Wall

Test Number	**C4 Charge Weight (g)**	**C4 Charge Distance (m) (ft)**	**Deflect. (cm)**	**Deflect. (in)**	**Average Pressure (kPa)**	**Average Pressure (psi)**
1	400	13.71 (45)	3.475	1.368	93.010	13.490
2	500	13.71 (45)	3.868	1.523	98.664	14.310
3	600	13.71 (45)	4.984	1.962	107.145	15.540
4	650	13.71 (45)	5.787	2.278	110.730	16.060
5	900	9.14 (30)	7.867	3.097	176.230	25.560

As the results show, the wall was able to withstand up to 176.23 kPa (25.56 psi) without failing structurally and having a maximum deflection of 7.867 cm (3.097 inches) as shown in Figure 11. However, all of the bolts connecting the top channel of the wall frame and the channel holding the oak board size adjustment progressively sheared off during testing. This is not a cause of concern since the roof bolts were still in place and are what will be used to secure the wall to a mine roof. The shearing of the bolts may have also influenced the amount of deflection that occurred in the system. The results show that the amount of deflection increased with pressure.

Two approximately 76.2 and 30.5 cm (20 and 12 inch) cracks developed following the final test in the center polycarbonate panel. There was also a smaller three inch crack which developed from previous testing; however, this crack never increased in size throughout all the tests. The large crack was a direct result of testing, but the three inch crack is believed to have been creating by over tightening the bolts against the polycarbonate. This may have also been a factor in the development of the large cracks following the final test since the cracks originate from the bolts. As a result, it is recommended that the bolts be hand tightened against the polycarbonate followed by a one second pulse from a 406.7 N-m (300 ft-lbs) impact wrench to avoid over tightening.

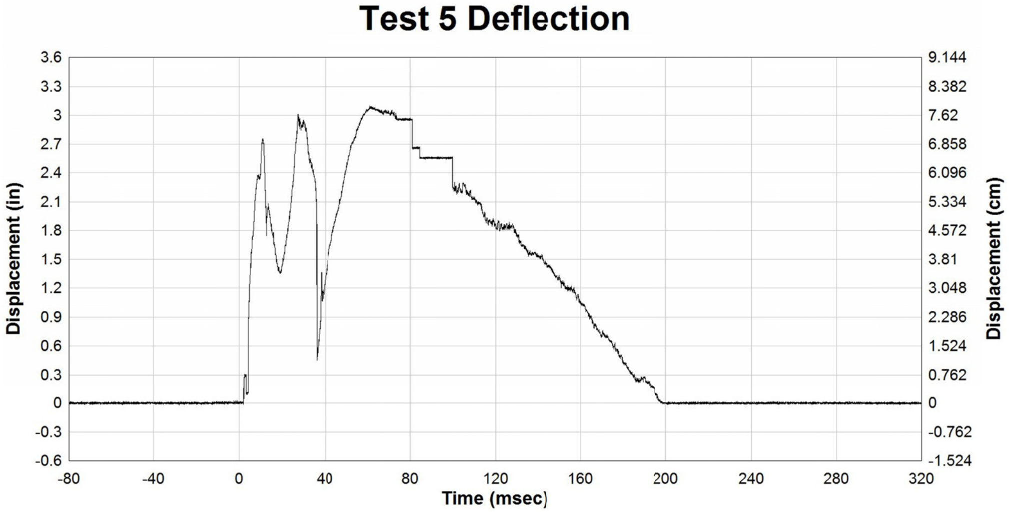

Fig. 11. Deflection at the middle of the center panel for Test 5 of the quarter scale setup

3. Conclusion

The purpose of the research documented in this paper was to develop a component for a new alternative to refuge options currently available to help protect trapped miners unable to escape in the event of a mine explosion. The polycarbonate safe haven wall described in this paper can offer miners protection while also aiding mine rescue teams locate trapped miners easier through the transparent polycarbonate panels. The polycarbonate safe haven wall also provides cost advantages compared to currently used refuge alternatives. The polycarbonate panels used for constructing the wall, although costly, are detachable and movable. Since the panels consist of half of the material price, this can be a great advantage. Bulk ordering materials for constructing and equipping the safe havens also help decrease costs, making an installed safe haven wall very cost competitive with current refuge alternatives.

The final design modeled with the MSHA prescribed waveform all had stresses within the elastic range of the materials (Perry & Meyr, 2013). When this same design was modeled and subjected to the waveforms generated from explosion testing, there was slight permanent deformation which was not evident in the testing. When comparing the explosion tests to the models, it is evident that the models are conservative. Therefore, one can extrapolate the conservative results from the scaled testing and model validation to the MSHA defined curve models with greater confidence. Numerous tests show that the wall is elastic in nature and can survive a 103.4 kPa (15 psi) explosion many times.

This paper provides the validation of a successful 103.4 kPa polycarbonate safe haven wall design through construction and testing. In all, the wall was tested nine times and demonstrated that it is a strong design capable of withstanding multiple blasts up to 176.23 kPa. Even though the pressure versus time waveform is still not where it needs to be to meet MSHA regulation, further research will have to be performed to develop a method in which to increase the duration of the blast.

Acknowledgements

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