2013

DEVELOPMENT OF 15 PSI SAFE HAVEN POLYCARBONATE WALLS FOR USE IN UNDERGROUND COAL MINES

Rex Allen Meyr Jr.
University of Kentucky, ram9q5@mail.missouri.edu

Recommended Citation

Meyr, Rex Allen Jr., "DEVELOPMENT OF 15 PSI SAFE HAVEN POLYCARBONATE WALLS FOR USE IN UNDERGROUND COAL MINES" (2013). *Theses and Dissertations--Mining Engineering*. 3.
https://uknowledge.uky.edu/mng_etds/3

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Rex Allen Meyr Jr., Student

Dr. Kyle A. Perry, Major Professor

Dr. Thomas Novak, Director of Graduate Studies

DEVELOPMENT OF 15 PSI SAFE HAVEN POLYCARBONATE WALLS FOR USE IN UNDERGROUND COAL MINES

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering in the College of Engineering at the University of Kentucky

By

Rex Allen Meyr Jr.

Lexington, Kentucky

Director: Dr. Kyle A. Perry, Assistant Professor of Mining Engineering

Lexington, Kentucky

2013

ABSTRACT OF THESIS

DEVELOPMENT OF 15 PSI SAFE HAVEN POLYCARBONATE WALLS FOR USE IN UNDERGROUND COAL MINES

Abstract

Following three major mining accidents in 2006, the MINER Act of 2006 was enacted by MSHA and required every underground coal mine to install refuge alternatives to help prevent future fatalities of trapped miners in the event of a disaster. The following research was performed in response to NIOSH's call for the investigation into new refuge alternatives. A 15 psi safe haven polycarbonate wall for use in underground coal mines was designed and modeled using finite element modeling in ANSYS Explicit Dynamics. The successful design was tested multiple times in both half-scale and small scale using a high explosive shock tube to determine the walls resistance to blast pressure. The safe haven wall design was modeled for an actual underground coal mine environment to determine any responses of the wall within a mine. A full scale design was fabricated and installed in an underground coal mine to determine any construction constraints and as a final step in proof of concept for the safe haven design.

KEYWORDS: coal mining, refuge alternatives, mine safety, modeling, explosive driven shock tube testing

Rex Meyr

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By

Rex Allen Meyr Jr.

Dr. Kyle Perry

Director of Thesis

Dr. Thomas Novak

Director of Graduate Studies

I can do all things through Christ who strengthens me. Philippians 4:13

ACKNOWLEDGMENTS

I would like to start by thanking my family. Mom and Dad, thanks for always being there for me and for helping mold me into the man I am today. I could not have made it this far without your love and support. To my sister Rachael, thanks for your encouragement and motivation to help me strive to be the best person I can possibly be. I love you all very much.

Many thanks to all my fellow graduate students who helped me perform construction and testing during my project. Josh Hoffman, Josh Calnan, John Rathbun, Kevin Harris, Mike (Jan) Raffaldi, and Adam Gamblin, your help was much appreciated.

Thanks to all the Mining Engineering Department for the help and knowledge you provided me during my time at the University of Kentucky. Special thanks to Braden and Dr. Novak for serving on my committee and helping critique my work to make it better.

Special thanks go to Ed Thompson. You were very instrumental in helping me along the way of my studies with knowledge about all aspects of life as well as helping me in my search for employment. Thank you.

Also, big thanks to Braden. Thanks for bringing Kyle to UK back in the day and thus, allowing me to come study under him. Thanks for all the help with the project both in the office and at the mine. Also, I appreciate your help and effort in my job search. Thanks again.

Finally, I would like to thank my advisor/cousin-in-law, Kyle. Thank you for providing me the opportunity to continue my education with you at UK. Thank you for

all your help and guidance with school as well as life in general. Thank you for teaching me how to put two spaces after period. There are more things than I can list that you helped me with while I was UK. I'm sorry I couldn't stay longer. I know I have a great mentor and friend in you always. Thank you again for everything.

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CHAPTER 1. INTRODUCTION

1.1 Introduction

From 1900 to 2006, there were 513 United States underground coal mining disasters or incidents with five or more fatalities, almost 90% due to explosion or fire, resulting in 11,606 coal miners losing their lives (CDC, 2009). From the subsequent legislation passed after these disasters, safety has improved and disasters have decreased from a high of 20 in 1909 to an average of one every four years during 1985 – 2005 (CDC, 2009). Three major incidents claiming 19 miners in the U.S. in 2006 again opened the eyes of legislators and regulators to the deficiencies in safety in underground coal mines and the need for new regulations to help aid in the survival of potentially trapped miners. Even though some form of refuge alternatives have been around since the beginning of the 20th century, one of the major parts of the most recent legislation, the MINER Act of 2006, requires refuge alternatives to be placed in every underground coal mine to help facilitate the survival and rescue of trapped miners. The term refuge alternative is a broad term that encompasses any alternative such as: refuge chamber/station/bay, safe haven/room, in-place shelters, etc.

1.2 Prior Safe Havens

The idea of using safe havens in underground mining for safety of miners in the event of emergency dates back over a hundred years. The U.S. Bureau of Mines first advocated the use of refuge chambers in 1912 to fight mine fires (Rice, 1912). Historically the use of refuge chambers have been more prevalent in underground metal/nonmetal mines, resulting in a significant knowledge and technology gap in coal mines where refuge alternatives are now required (NIOSH, 2007). Rescue (refuge) chambers originated from the practice of entrapped miners barricading themselves in a good air region in order to separate themselves from a region of fire and smoke (USBM, 1983). These barricades consisted of concrete blocks or brattice cloth fastened to the ribs, roof, and floor to help isolate the miners and the breathable air from the contaminated air (NIOSH, 2007). These practices have evolved into providing prepared barricaded sites such as chambers in mines with the necessary supplies to aid miners' survival until rescued.

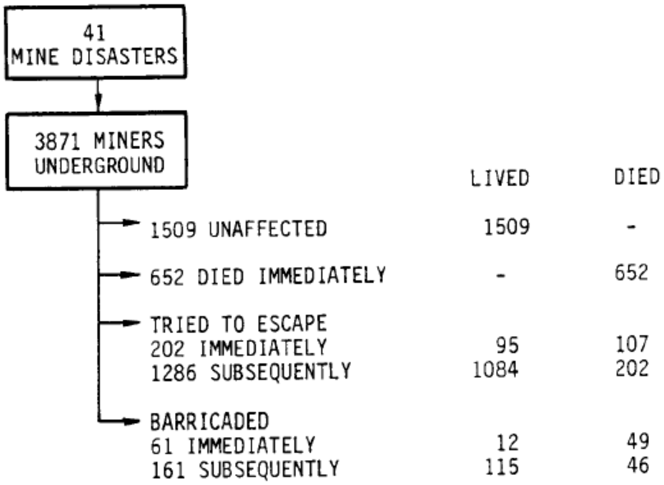
Through the years, mining methods, equipment, and regulations have gone through major changes thanks to advancing technology, resulting in a lower frequency and severity of mine fires and explosions. The evolution of barricading to the current safe havens is also a direct result of technology. Barricading in the 1900 – 1920s was based mainly on intuition and hearsay because investigations into the causes of explosions were still developing (USBM, 1983). Technological advances from the early 1920s through World War II helped the industry gain an understanding of the causes for explosions and how to better prevent them. Barricading was also made part of training programs by both the USBM specialists and progressive operators (USBM, 1983). By training miners on the proper location and method to barricade, their likelihood of survival in the event of having to barricade from an explosion or fire greatly increased. However, further advances in technology provided miners with properly designed refuge chambers that improved upon barricades in terms of both better construction and lesser dependence on prompt rescue (USBM, 1983). Several small refuge chambers were built in some coal mines during the late 1930s and early 1940s that were able to save lives

(Harrington and Fene, 1941). In addition, a number of large refuge chambers were built by Harwick Coal and Coke Co. in the Harwick Mine (Bauer and Kohler, 2009). The chambers measured 75 feet long, 8 feet high, and 11 feet wide, cut out of coal, and connected to the surface by two boreholes used for air, communications, food, and water (Harrington and Fene, 1941). These chambers are the first documented large permanent shelters built in the U.S.

Beginning in 1947, the coal mining industry began mechanizing, moving from picks and shovels to powered continuous miners. The new technological advancements presented the mines with new problems and less understanding of their potential contribution to fires and explosions. This continued until the Federal Mine Safety and Health Acts of 1969 and 1977 were implemented, which led to a greater understanding of mining practices and enforcement of them (USBM, 1983). For the first time, many mining operations were receiving fines for violations and frequently having to withdrawal miners due to unsafe conditions (USBM, 1983). As a result, the U.S. Bureau of Mines awarded five major contract efforts that were completed between 1970 and 1983 that addressed mine rescue and survival, the design of explosion-proof bulkheads, post survival, rescue research needs, and guidelines for rescue chambers (Bauer and Kohler, 2009). Out of the research efforts, a refuge chamber was constructed in NIOSH’s Bruceton Safety Research Coal Mine as shown in Figure 1.1 (Bauer and Kohler, 2009). The research efforts were unable to identify one specific component that would ensure survival during a mine disaster. However, it was determined that survival was based on a set of subsystems that included escape, rescue, communications, breathable air, and barricading (refuge) (Bauer and Kohler, 2009).

Figure 1.1. Refuge Chamber Located in Bruceton Safety Research Mine (Bauer and Kohler, 2009)

The U.S. Bureau of Mines collected data from 41 mine fires and explosions from 1940 – 1980 and the number of lives that could have possibly been saved by barricading. The data in Figure 1.2 shows the actions of miners for the 41 fires and explosions in which it is believed that barricading was an appropriate safeguard, 14 fires and explosions in which some miners barricaded and 27 others in which barricades may have saved lives (USBM, 1983). The data in Figure 2 shows that fewer than one in seven miners who had a choice to barricade or escape decided to barricade, subsequently, one out of every four miners who chose to escape died in the attempt (USBM, 1983). From 1940 – 1980, barricading saved 127 lives. Many of the men who were saved attribute their survival to having been trained in barricading (USBM, 1983). This illustrates how important the proper training and implementation of a barricade or safe haven helped facilitate survival and rescue during a mine disaster to save lives. Although barricading was a common practice for much of the 20th century, there is no evidence to support its use in modern mining operations, and NIOSH does not consider it to be a viable refuge alternative (NIOSH, 2007). As a result, the idea of barricading to help save lives has now evolved into refuge alternatives used today that are required to maintain a life-sustaining environment for trapped miners.



	LIVED	DIED
1509 UNAFFECTED	1509	-
652 DIED IMMEDIATELY	-	652
TRIED TO ESCAPE		
202 IMMEDIATELY	95	107
1286 SUBSEQUENTLY	1084	202
BARRICADED		
61 IMMEDIATELY	12	49
161 SUBSEQUENTLY	115	46

Figure 1.2. Actions of Miners in 41 fires and explosion, 1940 – 1980 (USBM, 1983)

1.3 The MINER Act

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 MINER Act provides regulations requiring the use of refuge alternatives or safe havens to help improve the chances of survival of miners in the event of a disaster. Section 13 states that the National Institute of Occupational Safety and Health (NIOSH) shall conduct research concerning the utility, practicality, survivability, and cost of various refuge alternatives in an underground coal mine environment, including already commercially-available portable refuge chambers (Department of Labor, 2006). 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 and the training of miners in their use (Department of Labor, 2009). In establishing the Final Rule, MSHA reviewed NIOSH’s report on refuge alternatives practicality along with many underground mine accident reports from 1900 through 2006. While reviewing the reports, it was determined that refuge alternatives could have potentially saved between 25 and 75 percent of lives in mining accidents during the concerned time period, or an average of one to three lives every two years. However, the potential for refuge alternatives to save lives will only be realized once mines develop comprehensive escape and rescue plans incorporating refuge alternatives (Department of Labor, 2009).

The Final Rule also defines the purpose, scope, and design requirements for refuge alternatives. A refuge alternative is defined as “a protected, secure space with an isolated atmosphere and integrated components that create a life-sustaining environment for persons trapped in an underground coal mine” (Department of Labor, 2009). An approved refuge alternative’s purpose is to “provide a life-sustaining environment for persons trapped underground when escape is impossible” (Department of Labor, 2009). Refuge alternatives can also be used to help facilitate escape by sustaining trapped miners while they wait for communication regarding escape or rescuers arrive (Department of Labor, 2009). However, even though refuge alternatives have the potential to save a trapped miner, they are always considered a last resort for a person unable to escape in the event of an emergency, escape is always the highest priority. For a refuge alternative to be used for its designed purpose, it must be designed to withstand 15 pounds per square inch (psi) overpressure for 0.2 seconds (Department of Labor, 2009). This design requirement comes from a NIOSH recommendation after performing tests at its Lake Lynn Laboratory and studying typical blast wave propagation in an underground mine.

1.4 Modern Safe Havens

Driven by technology, regulations, and the will to survive, early 20th century block wall and brattice cloth barricades have evolved into many forms of safe havens to help facilitate survival in the event of a mine disaster. The two main types of refuge alternatives used in underground coal mining today are permanent and portable alternatives. There are many different designs, sizes, and manufacturers of each alternative, thus, giving each mine the ability to choose the proper fit for their mining operation.

1.5 Permanent Safe Havens

Permanently placed safe havens, or in-place shelters, are generally developed by using existing parts of the mine as part of the structure and located adjacent to the main travel way. Two common ways to create an in-place shelter are to install a bulkhead at either end of a crosscut to isolate the area, or mining into a block of coal and installing a bulkhead to isolate the dead-end heading (NIOSH, 2007). Figure 1.3 shows an overview of how a permanent safe haven can be constructed within a mine. In either circumstance, the isolated area is sealed to maintain a stable life-sustaining atmosphere. To provide a life-sustaining atmosphere, CO_2 scrubbers, fresh air, food, and water needs to be provided to the miners inside the isolated shelter for a NIOSH recommended minimum 48 hours.

Ideally, this is achieved by having a borehole drilled from the surface to the isolated area through which supplies can be passed to the miners inside the refuge (DJF Consulting Limited, 2004). Conversely, air can be supplied to the shelter via compressed air lines running throughout the mine, although not all mines have compressed air lines, and consideration must be given to the location of the compressor to ensure its integrity in an emergency situation (DJF Consulting Limited, 2004). Without a surface borehole, the shelter will also need to be stocked with food and water rations to sustain the maximum occupancy for 48 hours.

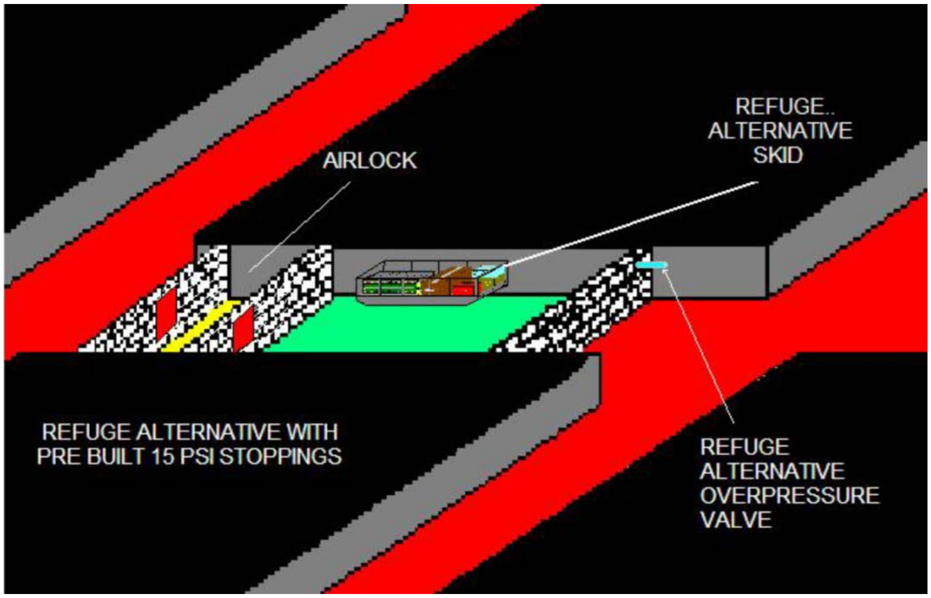


Figure 1.3. Permanent Safe Haven Overview

The structure of the in-place shelter must also be fire resistant and have strength to withstand a certain blast pressure that may be encountered during a mine disaster. The recommended values for these parameters along with many other design and performance specification for refuge alternatives have been determined by NIOSH. These recommended values have been chosen based on the literature, practices in other countries, guidance obtained from the study of non-mining applications, and explosion testing performed by NIOSH at Lake Lynn Laboratory (NIOSH, 2007). NIOSH recommends that any structure must have a fire resistance of 300° F for three seconds and the strength to withstand a blast pressure wave that rises to 15 psi in 0.10 seconds and then returns to 0 psi after another 0.10 seconds (NIOSH, 2007). These values along with many other design and performance specification for refuge alternatives can be found in Appendix E. Further explanation of all refuge alternative specifications is documented in The Mine Safety and Health Administration 30 CFR Parts 7 and 75, “Refuge Alternatives for Underground Coal Mines Final Rule”.

Since permanent safe havens are constructed using part of the existing mine, adequate planning needs to be performed to ensure proper placement and spacing of refuges as the mine develops. The recommended spacing of refuge alternatives is every 1000 – 2000 feet from the working face or at a distance that a miner could reasonably travel in 30 – 60 minutes under expected travel conditions (Department of Labor, 2008). The presence of smoke, lower seam heights, and difficult bottom conditions will all increase travel times. Therefore, the maximum spacing of refuge alternatives should depend on projected travel time rather than actual travel distance (NIOSH, 2007). The 30 – 60 minute travel time is based on the oxygen producing capabilities of traditional self-contained self-rescuers (SCSR) that miners would be using to breathe (NIOSH, 2007). However, it is always advantageous to locate refuge alternatives in the context of an escape and rescue plan for each mine (NIOSH, 2007).

1.6 Portable Safe Havens

The alternative to providing a permanent safe haven constructed within the mine is to use a portable chamber that is manufactured off-site, delivered to the mine, and moved to its appropriate location. In response to the MINER Act of 2006, every underground coal mine was required to install refuge alternatives and according to manufacturer's reports, 90 percent of chambers ordered as of 2008 were portable (Bauer and Kohler, 2009). This shows that portable chambers are the popular choice for mining operations. A portable chamber has a great logistical advantage over a permanent refuge since it can be advanced with the working section or moved from an area of the mine that is being sealed off. The investment of time and money is also much less when a chamber can be reused in different parts of a mine and requires less area for placement. However, the design of temporary havens require more expertise and practicality to suit the rapidly moving working place while still providing a life-sustaining environment in the event of a fire or explosion (DJF Consulting Limited, 2004).

The most common types of portable safe havens are chambers consisting of manufactured rigid or inflatable vessels housed in a steel structure and deployed when needed (NIOSH, 2007). These types of chambers contain all the equipment and supplies required to provide a life-sustaining environment to trapped miners for at least 48 hours. Figures 1.4 – 1.7 show an example of this type of safe haven. Figure 1.4 shows the rigid, explosion-resistant steel container that contains a folded up inflatable fresh air bay as shown in Figure 1.5. In the event of an emergency, the inflatable fresh air can be inflated in minutes out of the steel container using compressed air from cylinders as shown in Figure 1.6 (Chadwick, 2009). Figure 1.7 shows how the inside of an inflated fresh air bay would look.

Figure 1.4. Inflatable Fresh Air Bay Skid Storage Container

Figure 1.5. Inflated Inflatable Fresh Air Bay

Figure 1.6. Fresh Air Bay Inflated Out of the Fresh Air Bay Skid

Figure 1.7. Inside Inflated Fresh Air Bay

Another type of portable refuge chamber is an explosion resistant, steel walk-in chamber. This type of chamber, unlike an inflated fresh air bay, is designed to withstand a 15 psi blast pressure. The chamber requires no deployment of any kind and is fully equipped to provide a life-sustaining environment. Chambers come in standard sizes along with custom sizes to fit the needs of individual mines. Figures 1.8 and 1.9 show what an explosion proof steel refuge chamber looks like from the outside and inside, respectively. Both types of portable chambers described above, along with any other portable chamber used in an underground coal mine, must all also meet the same design and performance requirements suggested by NIOSH as the previously discussed permanent refuge alternatives. Finally, as suggested by their name, all portable refuge alternatives have the option of being equipped with wheels or skids for ease of movement.

Figure 1.8. Explosion Proof Steel Refuge Chamber

Figure 1.9. Inside of Steel Refuge Chamber

1.7 Utility of Refuge Alternatives

The requirement of refuge alternatives in all underground coal mines instituted by the passing of the MINER Act in 2006 triggered research not only into the design and performance specifications of alternatives but also into the utility, practicality, and survivability. Refuge chambers utility, or usefulness, has long been debated in the U.S. dating back to the passage of the Coal Mine Health and Safety Act of 1969, PL 91-173, which authorized the Secretary of Labor to order the erection of rescue chambers for persons to go in the event of an emergency (Bauer and Kohler, 2009). However, despite

PL 91-173 and significant research performed by the U.S. Bureau of Mines over 30 years ago, refuge alternatives have not been embraced by industry, labor, or government (NIOSH, 2007). The past and present focus was and is to escape the mine.

NIOSH performed an extensive study of past underground coal mining disasters from 1970 – 2006 to determine the utility of refuge alternatives to aid in the survival of miners in the event of a disaster (Bauer and Kohler, 2009). From the study, it was difficult to determine whether a refuge alternative would have altered the outcome of a disaster due to the small sample size and differentiating circumstances for each disaster. In turn, it was hard to make a case either way for the utility of safe havens or their use. However, the three mining disasters in 2006 helped refocus the study to determine if a refuge alternative would have been useful in any of the previous disasters. It was determined that of the 252 fatalities from the 38 disasters studied, 74 might have been positively impacted by the presence of a refuge alternative, resulting in the potential survival of the miners (Bauer and Kohler, 2009). The group of miners that might have been impacted the most by a safe haven was those who died while trying to escape and/or barricade (Bauer and Kohler, 2009).

As a result of the research, NIOSH believes there is significant opportunity in the utility of refuge alternatives to facilitate escape and also serve as a safe haven of last resort when escape is impossible (NIOSH, 2007). To realize the full potential of any refuge alternative to save lives, it must be integrated into a comprehensive escape and rescue plan developed by mine operators (Bauer and Kohler, 2009). This further depends on the suitability of the engineering design and specifications for each refuge application within the escape and rescue plan. In turn, the opportunity for a safe haven to save lives in the event of a mine disaster justifies their utility in underground coal mines (Bauer and Kohler, 2009).

1.8 Practicality of Refuge Alternatives

The practicality of refuge alternatives depends on whether they can be successfully implemented, moved, and maintained in an underground coal mine (Bauer and Kohler, 2009). Refuge alternatives are available commercially and have been successfully installed in underground coal mines in other countries and in the U.S., but there is no documentation on the successful use in the event of disaster (NIOSH, 2007). This is due to the recent regulation and subsequent implementation of safe havens in underground coal mines and the fortunate lack of mine disasters requiring their use. Concerns have been raised that moving refuge alternatives with advance and retreat of mining could be difficult and possibly impractical, although, after thorough investigation it was determined that moving refuge alternatives can be done safely and practicably (NIOSH, 2007). The concerns over and lack of documented successful use of safe havens do not outweigh their utility to save lives. Therefore, NIOSH determined that refuge alternatives are practical for use in most underground coal mines (Bauer and Kohler, 2009).

1.9 Survivability of Refuge Alternatives

Survivability of refuge alternatives focuses on the ability of a refuge to survive an initial explosion and still provide miners with a life-sustaining environment and basic human needs (NIOSH, 2007). Any safe haven currently used in an underground mine should meet these and other specifications that were previously defined by NIOSH.

Many of the specifications depend on the engineering design of the structure to withstand a mine explosion and protect the life-sustaining systems within the refuge alternative. To help ensure the survival of a refuge alternative in the event of an explosion, the alternative should be positioned out of the expected direct explosion force path to minimize the probability of being struck by flying debris (Bauer and Kohler, 2009). The survivability of the life-sustaining systems within safe havens has been mostly solved by manufacturers. With the structural integrity and basic human needs successfully addressed, there is no reason to believe a refuge alternative could not sustain miners for the NIOSH recommended minimum duration of 48 hours (Bauer and Kohler, 2009).

1.10 The Use of Polycarbonate

The goal of this research is to utilize polycarbonate panels bolted to a steel frame to build a safe haven wall. The polycarbonate panels, with the structural support from the steel frame, will have to withstand a 15 psi blast similar to a mine explosion. This will not be the first use of polycarbonate by the mining industry or any other industry to mitigate blasts. Most notably, the civil construction industry has long used polycarbonate for blast mitigation. By definition, polycarbonate is any of various tough transparent thermoplastics characterized by high impact strength (Merriam-Webster Dictionary, 2013). While most annealed plate glass can only withstand a 2 psi blast pressure, polycarbonate panels can resists pressures up to about 30 to 40 psi depending on thickness (Ettouney et al., 1996). However, the possibilities of polycarbonate are still improving to include withstanding higher pressures. Much of the ability of each panel is highly dependent on the actual dimensions (Ettouney et al., 1996). Furthermore, the use or application of any polycarbonate to laminated glass has shown to provide one of the most economical and effective blast-resistant glazing constructions available (Norville et al., 2001).

1.11 Polycarbonate Use in Civil Construction

The use of polycarbonate for windows in the civil construction industry was spurred by the Oklahoma City bombing in 1995. Besides the shear destruction of buildings when an explosion occurs in a populated area, a vast amount of people in surrounding buildings are killed or injured by sharp edged shards flying from fractured window glass due to air blast created by the explosion (Ettouney et al., 1996). To help minimize and eliminate flying and falling glass shards during an explosion, properly designed blast-resistant glazing is used for protection (Norville et al., 2001). Polycarbonate and many other plastic materials do not typically fracture or tear under air blast pressure loading; therefore, it makes excellent blast-resistant glazing material (Norville et al., 2001). However, a disadvantage of polycarbonate not fracturing is that it tends to remain in one piece, similar to a car windshield, and can cause serious injury similar to a large flying object (Ettouney et al., 1996). As a result, the framing system surrounding the polycarbonate must be very strong to allow the proper stresses to develop that cause proper failure of the window to avoid injuries (Ettouney et al., 1996). The implementation of the correct framing along with polycarbonate panels has allowed the civil construction industry to build improved blast-resistant structures.

1.12 Polycarbonate Use in Mining Applications

The use of polycarbonate in the mining industry has been very sparse. Its primary use has been for luminaries and explosion-proof enclosures. In 1975, the Westinghouse

Electric Corporation was contracted to design and build a permissible ultraviolet lamp for mine inspectors to be able to identify fluorescence phosphor grains contained in permissible explosives (Ryan, 1977). Polycarbonate plastic was used to make the case for the light because of its superior mechanical properties and rating as a “self-extinguishing” under a flammability test (Ryan, 1977). Polycarbonate has also been used for windows and lenses built into luminaires, lighting fixtures mounted on coal mining machinery (Scott, 1982). The windows and lenses in the luminaires required more careful design than others because of the more severe thermal environments to which they were subjected (Scott, 1982).

Additionally, polycarbonate was used for the many explosion-proof enclosures within mines. An explosion-proof enclosure is defined by Title 30 of the Code of Federal Regulations (CFR), Part 18.2, as “…an enclosure that…is so constructed that it will withstand internal explosions of methane-air mixtures: (1) without damage to or excessive distortion of its walls and cover(s), and (2) without ignition of surrounding methane-air mixtures or discharge of flame from inside to outside the enclosure” (Scott, 1982). This definition includes several types of electrical equipment such as power enclosures, distribution boxes, splice boxes, and ballast boxes (Scott, 1982). Transparent polycarbonate windows and lenses were used to protect the face of electrical boxes to allow for the movement of electrical controls to be observed while voltage measurements are made at isolated test points (USBM, 1982). The polycarbonates transparency helps reduce the amount of time required to perform such tests by allowing miners to easily read the electric boxes.

Polycarbonate provides the civil construction and mining industry with transparent blast-resistant windows and lenses to better facilitate safety and working conditions. The same attributes described above of previous polycarbonate applications were important for the success of this research project. The transparency and lightweight of the polycarbonate compared to block walls that are normally built for safe havens are two of its greatest advantages. Transparency may reduce the possibility of claustrophobia in a safe haven and aid the rescue team's ability to quickly locate trapped miners in the event of an explosion, while lightweight panels will decrease injuries and construction time. Both advantages of polycarbonate will help increase productivity in the mine, help save lives, and reduce operation costs.

1.13 Research Objectives

The research described in the next several chapters investigates the design process of a new polycarbonate safe haven wall to be used in underground coal mines. Because of three mine disasters in 2006, the MINER Act of 2006 was established by MSHA to help improve safety in mines. The MINER Act also provided regulations for the implementation of refuge alternatives in all underground coal mines and set up funds for the research of new refuge alternatives. Current refuge alternatives are limited to permanent in-place shelters and various costly portable refuge chambers. The goal of the research was to design a cost effective safe haven that will help improve the overall safety of extracting coal in all seams and reduce operation costs which, in turn, will have a trickle-down effect on all citizens paying their electric bill.

The specific objectives of this research include:

- Design a polycarbonate wall system that can be constructed in a modular fashion with limited material handling using MSHA regulations for refuge alternatives and prior knowledge
- Model the designed polycarbonate wall system using ANSYS Explicit Dynamics and AutoDYN
- Construct the design and perform validation testing using an high explosive shock tube
- Model the polycarbonate wall system design for a typical coal mine environment using FLAC3D
- Develop a field ready system and install it in a chosen underground coal mine in less than one shift

CHAPTER 2. DESIGN

2.1 Introduction

The following thesis documents the research of the successful development of a 15 PSI safe haven wall system for use in underground coal mines utilizing polycarbonate panels and steel framing. The goal of the research was to create a more cost effective solution to current refuge alternatives while still providing the highest level of safety with the ability to expedite mine rescue teams' efforts in the event of an explosion. To accomplish this, the design incorporated expertise and materials from the civil construction industry which already uses many blast mitigation technologies. The use of blast resistant polycarbonate panels provide a light-weight and easily handled material for personnel constructing the safe haven walls. During construction of the prototype in an underground coal mine, there was far less material handling and transportation when compared to a block and mortar wall. The reduction of material handling may potentially reduce the number of slip/fall injuries which are among the most common injuries in underground coal mines.

To achieve structural safety and blast resistance, the safe haven wall system was designed and modeled in ANSYS Explicit Dynamics and AutoDYN to produce an adequate design capable of resisting a MSHA prescribed pressure versus time curve. The design was then modeled for its intended use in a coal mine environment using FLAC3D to ensure reactions into the mine geography were sustainable. Following successfully modeled designs, a wall was manufactured and tested using the high explosive shock tube facility in Georgetown, Kentucky. After the system passed laboratory explosive testing, a field ready system was developed and installed in an underground coal mine in Kentucky.

Once the wall design is considered permissible by MSHA, the wall designs will be a cost effective option for active coal mines to provide its miners a place to seek refuge in the event of an explosion.

2.2 Design and ANSYS Explicit Dynamics and AutoDYN Modeling

Design and modeling began with development of a safe haven wall system that can resist a 30 PSI blast load spanning 200 milliseconds which gives a safety factor of two to the 15 PSI MSHA requirement. The MSHA prescribed curve has a linear increase to 15 PSI at 100 milliseconds and then decreases linearly to zero at 200 milliseconds (Department of Labor, 2008). The wall system was designed using ProEngineer and then modeled in ANSYS Explicit Dynamics and AutoDYN. The designed system is a general single-degree-of-freedom design that is 20 feet long and 6 feet 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 systems initially considered for the design were Solid Square, Hollow Square and Rectangular tube, and W sections or I-beams. All support system elements were structural steel with an ultimate strength of 60 KSI. These supports are held in place by C shapes, or steel channels, on the top and bottom of the system which are bolted to roof and floor of the mine. The polycarbonate panels are bolted to the supports on the outby side of the frame. The supports are spaced no closer than 30 inches per MSHA code for minimum support spacing as to allow a stretcher to be passed through the door panel (Department of Labor, 2008).

The initial design was developed in ProEngineer and used eight Solid Square five inches by five inches supports consisting of six vertical pieces spaced on 48 inch centers and two horizontal pieces spaced at 72 inches. Polycarbonate panels one inch thick and 48 inch wide were then fastened to the outby side of the supports. Figure 2.1 shows the initial design with Solid Square five inches by five inches supports and one inch polycarbonate panels.

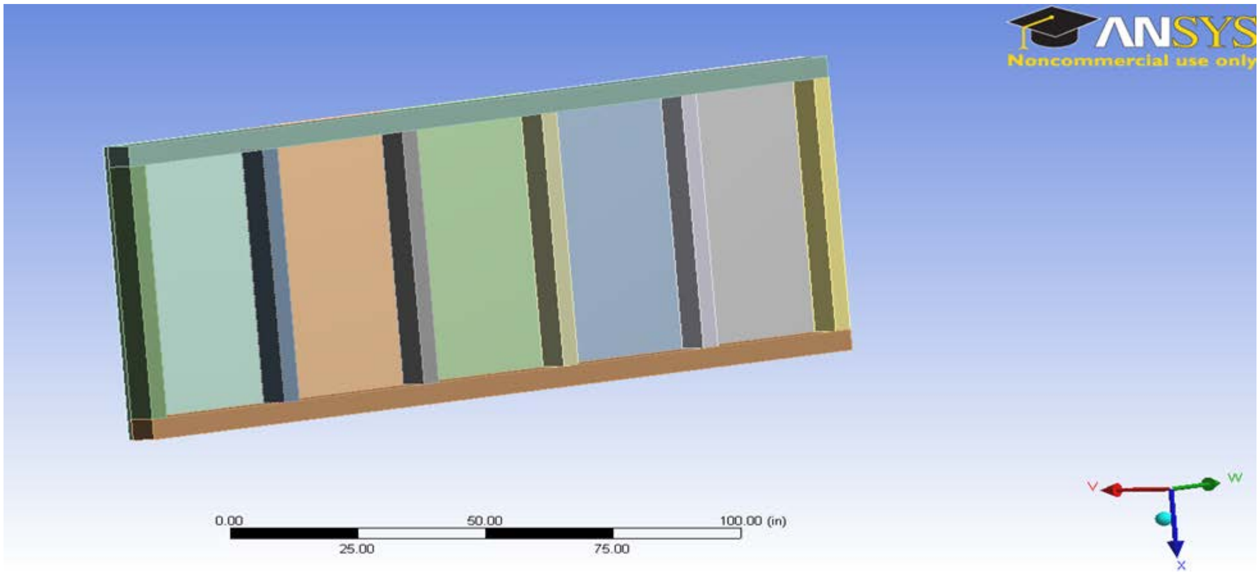


Figure 2.1. Initial Design with Solid Square five inches by five inches Supports and one inch Polycarbonate Windows

The design was then imported into ANSYS Explicit Dynamics where it was given parameters and setup for modeling. All connections within the system were bonded within the program to simulate being bolted together. The top and bottom of the system in contact with the surrounding rock were given fixed end-conditions to simulate being bolted into the ceiling and floor of a mine. The wall sides remained free as to force a one way reaction of the structure. The design was then subjected to 15 and 30 PSI loads over the 200 millisecond interval. The resulting deformations and stresses of the polycarbonate windows and steel frame are shown in Figures 2.2 – 2.5 and numerically in Table 2.1.

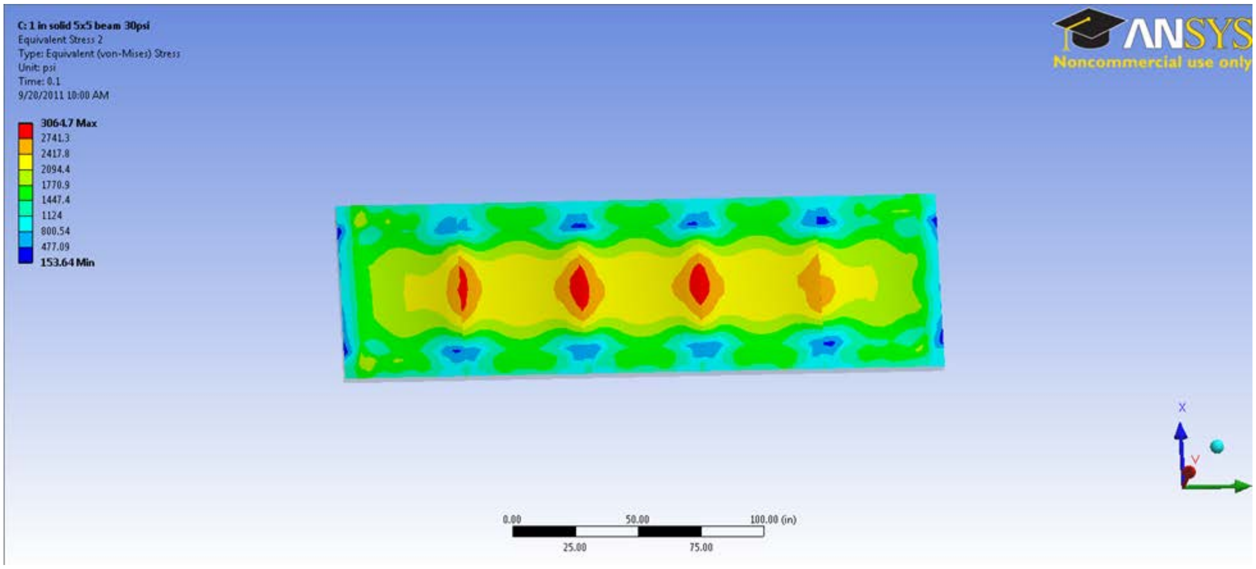


Figure 2.2. Stresses in the Polycarbonate Windows

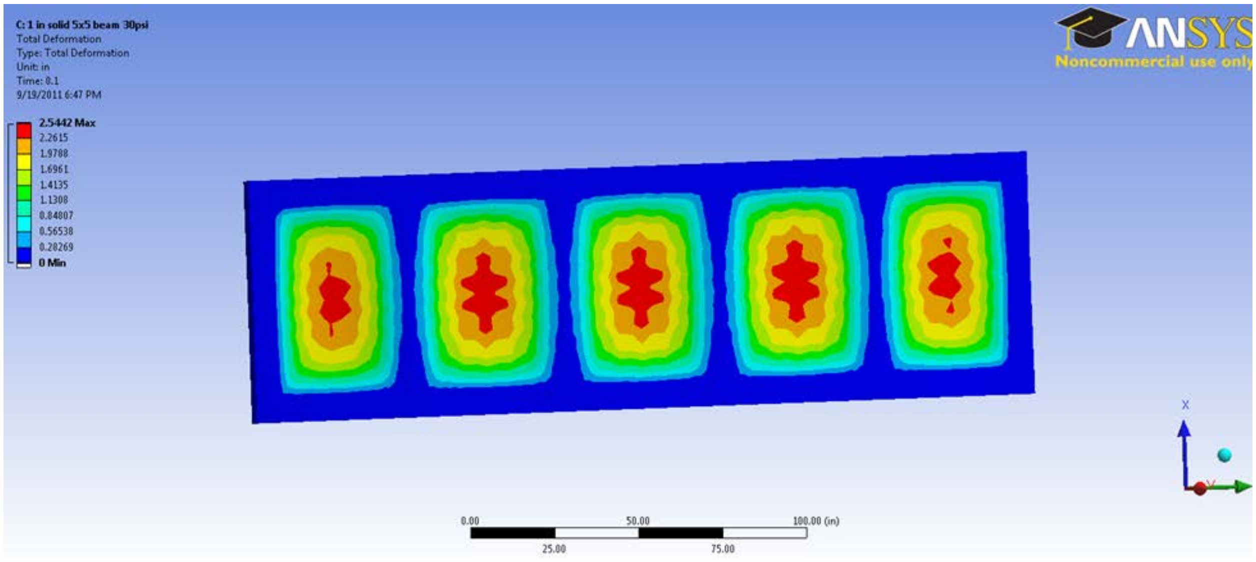


Figure 2.3. Deformation in the Polycarbonate Windows

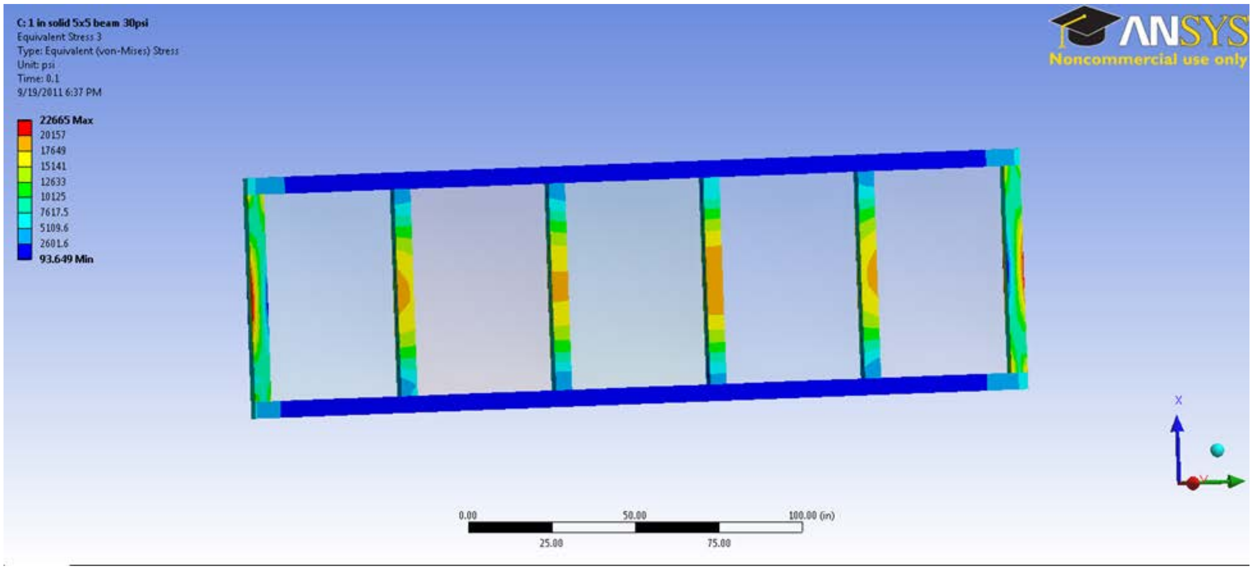


Figure 2.4. Stresses in the Solid Square Steel Supports

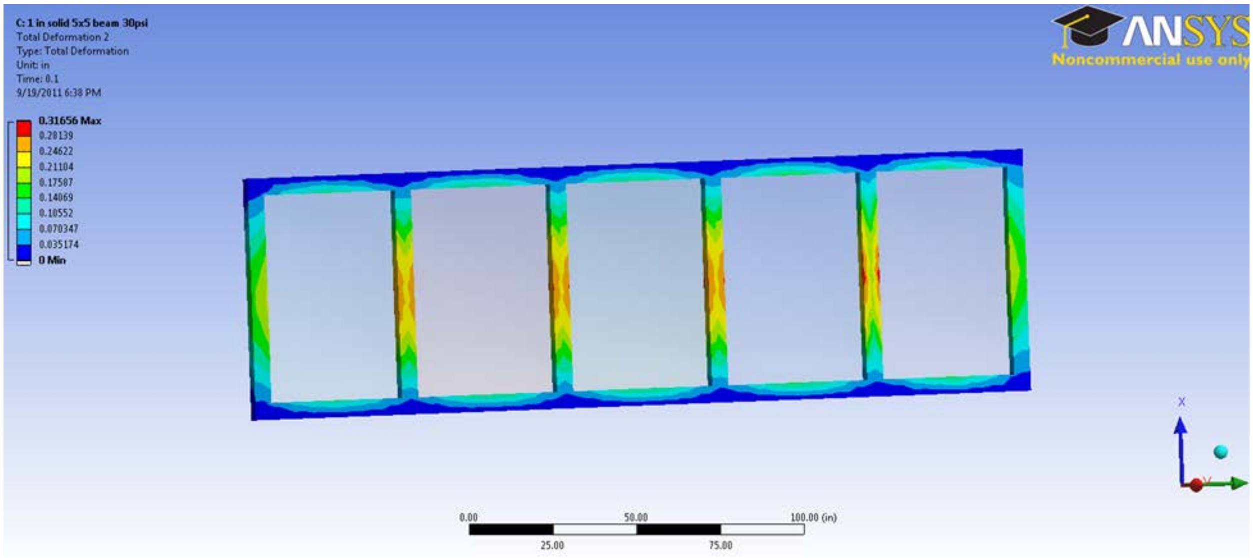


Figure 2.5. Deformation in the Solid Square Steel Supports

Table 2.1. Results from Initial Design at 30 and 15 PSI

Model #	Poly Thickness (in)	Blast Pressure (psi)	Max Deformation Support (in)	Max Deformation Poly (in)	Max Stress Support (psi)	Max Stress Poly (psi)
1	1	30	0.31656	2.5442	22665	3064.7
2	1	15	0.16622	1.9275	13370	1843.5

After modeling completion for the initial design, it was apparent that the design was successful. The materials did not break and the ultimate strengths of the materials were not exceeded. However, one of the goals of the project was for the wall to be easily constructed. With the Solid Square five inches by five inches weighing over 85 lb/ft the design would not have met that goal. Therefore, the design was altered to use Hollow Square and Rectangular tube to reduce the weight of the supports so that they can be easily handled by a few workers. The new system designs used Hollow Rectangular tube (HSS) and I-beams starting around the initial design size fitted between a channel at the top and bottom of the system. Using a channel to hold the vertical support system together brought the challenge of finding the right combination of depth of support that could fit into the allowable depth of the desired channel. This was much more challenging when trying to design a system using I-beams as the vertical support because of the limited number of shapes commercially available. These systems were based on 48 inch centers for the supports and polycarbonate windows with thicknesses of 1 to 2 inches and were subjected to a 30 PSI blast in 200 milliseconds. For the most part the designs did not fail, however the stresses in the supports exceeded the 60 KSI ultimate strength of the steel.

In attempt to distribute the large stresses the supports need to resist, the spacing between the vertical I-beam and HSS supports was reduced to the minimum allowable of 30 inches and the polycarbonate windows thickness was increased to 3 inches. In response, the stresses were reduced but they were still greater than the allowable stress for the steel in the supports. In an attempt to further improve the resistance, the supports were increased in size. This reduced the stress and gave results close to the allowable stress for the steel. However, the supports were still bulky and not meeting the goal of an easily constructed design. Furthermore, the designs using I-beams for supports resisted the stresses from the blast better than the HSS supports. Results for the reduced spacing at the 30 PSI pressure are shown in Table 2.2 below.

Table 2.2. ANSYS Modeling Results

30 in spacing min									
Run	**Channel**	**Support**	**Material**	**Poly Thickness (in)**	**Spacing (in)**	**Total Deformation Support (in)**	**Total Deformation Poly (in)**	**Total Stress Support (psi)**	**Total Stress Poly (psi)**
3	MC 7x22.7	HSS 6x6x0.625	struc steel	2	30	4.585 piece broke	2.4946	111020	11771
4	C 12x30	HSS 6x4x0.375	struc steel	3	30	11.651 broke	2.4158	99841	12394
5	MC 4x13.8	HSS 6x4x0.5	struc steel	2	30	0.808	2.2927	493550	11709
6	C 12x30	HSS 7x4x0.5	struc steel	3	30	8.1231	1.9472	100125	12272
7	MC 4x13.8	HSS 8x4x0.5	struc steel	2	30	3.3451	1.5013	391270	13917
8	C 15x50	HSS 12.5x13.75x0.625	struc steel	2	30	7.5321	1.5707	92119	11645
9	MC 12x50	W 10x77	struc steel	2	30	1.0806	1.4569	86866	6095.6
10	C15x50	W 12x152	struc steel	3	33	0.67482	1.6926	80938	10628
11	C 15x50	W 12x152	struc steel	2	33	10.923 broke	1.8621	100075	7428.1
12	C15x50	W12x152	struc steel	3	30	0.61711	1.5304	75144	6007
13	C 15x50	W 12x152	struc steel	2	30	1.2784	1.5931	77590	8098.3
14	MC 18x58	W 14x283	struc steel	3	30	10.991 broke	1.228	100023	9503

To further reduce the weight of the steel supports, hollow structural sections were substituted into the design. The design was also altered from previous designs by adding an additional support directly behind each original support. Two supports were put back to back to allow for easier construction and greater distribution of the stresses incurred from the blast pressure. As a result, after several iterations, the design was able to successfully resist the required 30 PSI in 200 millisecond blast pressure when a safety factor of two is applied to the pressure. The successful design consists of 14 hollow structural sections 8 x 4 x 0.625 inch vertical supports held in place by a C10 x 30 channel at the top and bottom. Polycarbonate panels with a thickness of one inch were bolted on the outside of the frame to complete the design. Figure 2.6 shows the completed design from the exterior side allowing one to see the double supports. In Figure 2.7, the red circle illustrates how the supports fit in the channel and how the polycarbonate is attached to the supports. Figures 2.8 – 2.11 show the resulting deformations and stresses in the polycarbonate windows and steel supports.

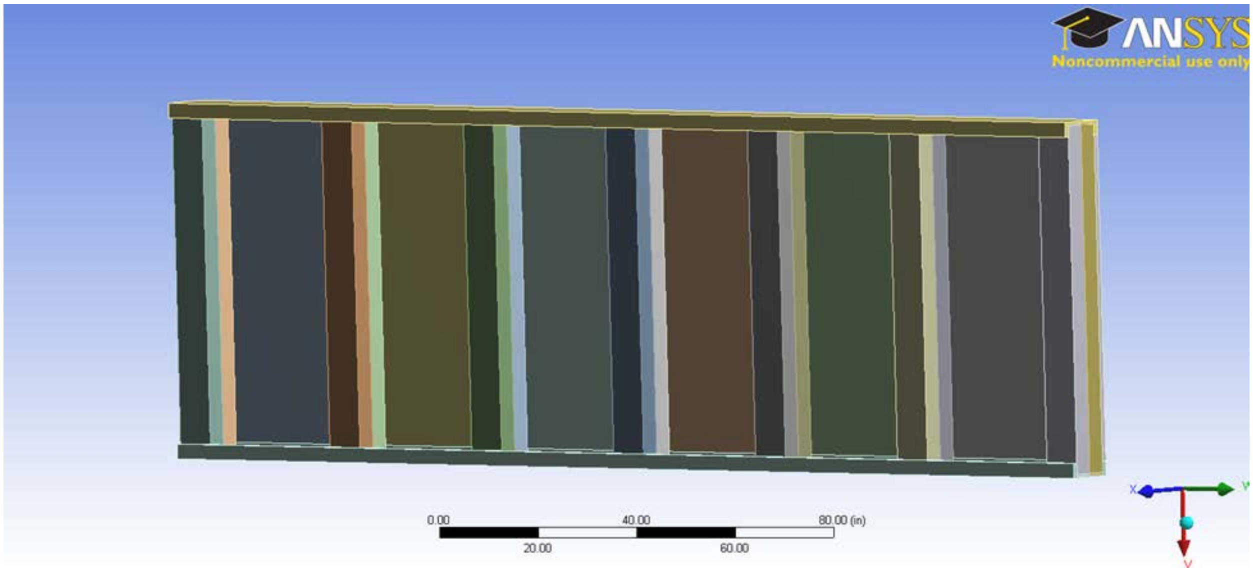


Figure 2.6. Completed Successful Design

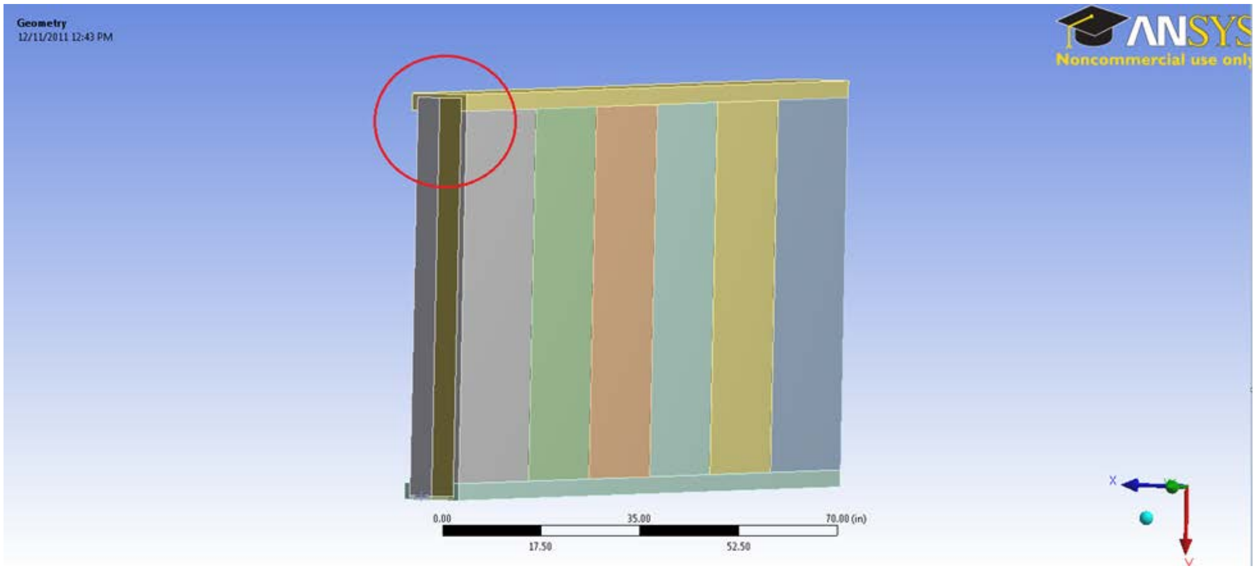


Figure 2.7. Support Framing and Polycarbonate Interaction

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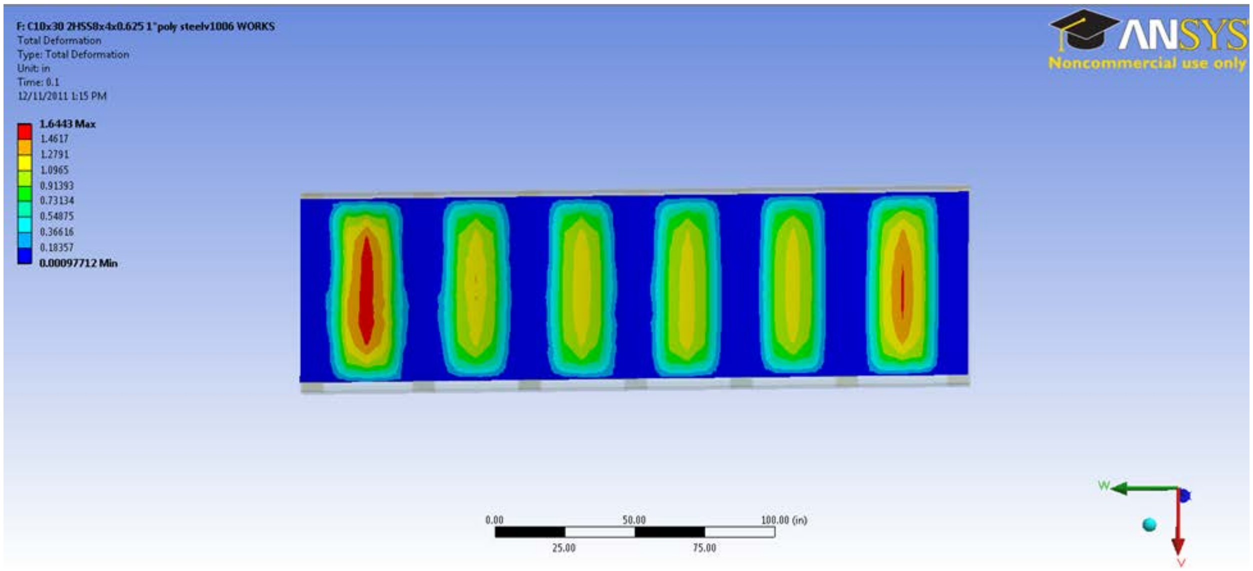


Figure 2.8. Deformation in Polycarbonate Panels

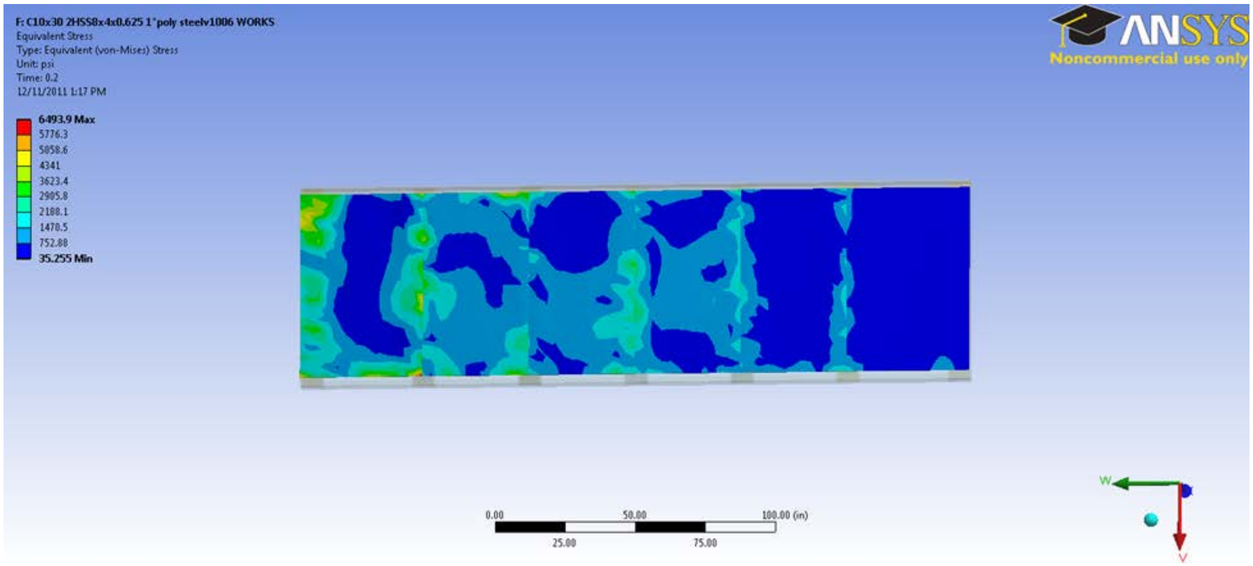


Figure 2.9. Stresses in Polycarbonate Panels

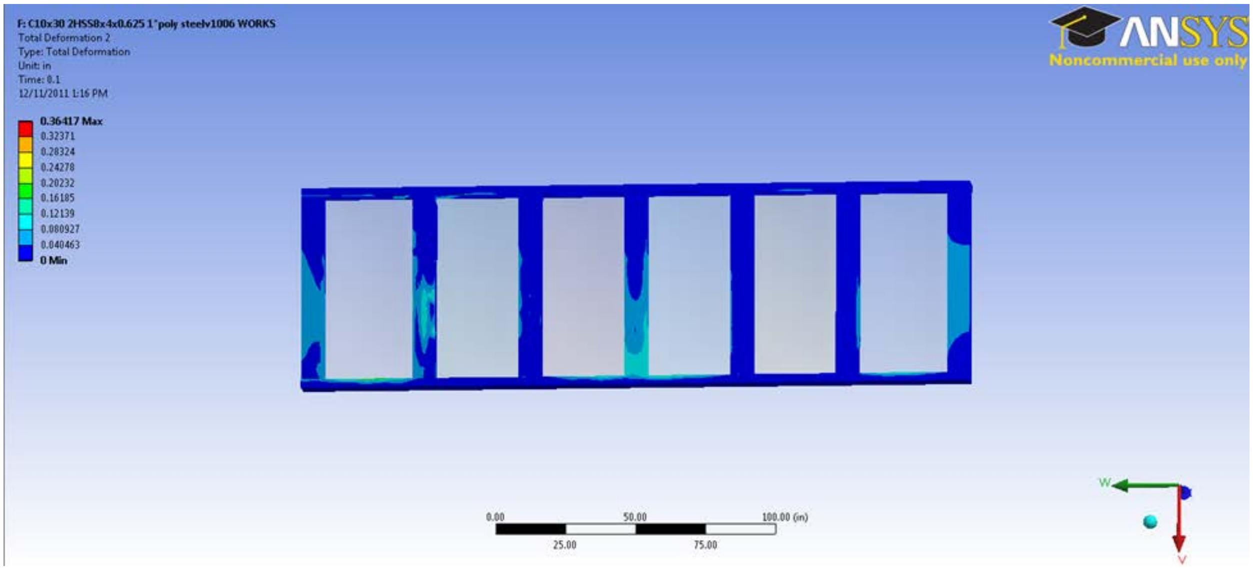


Figure 2.10. Deformation in Steel Supports

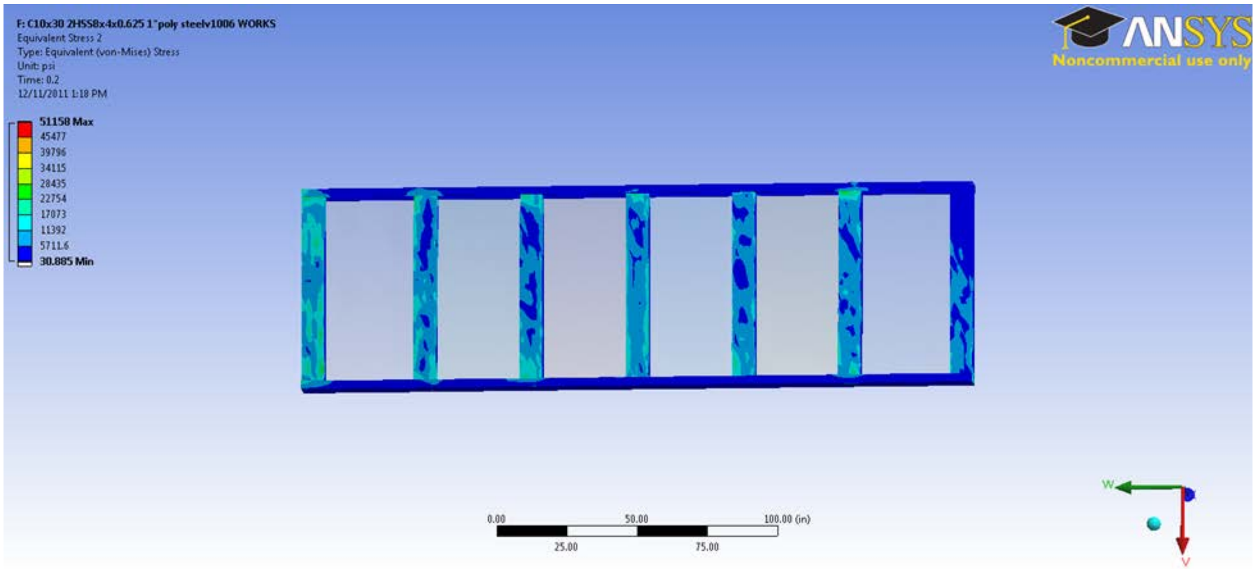


Figure 2.11. Stresses in Steel Supports

The completed design meets the goal of being a lightweight and easily constructed safe haven wall system. The supports weigh roughly 42 pounds per foot; therefore, a six foot support weighs 252 pounds, which a two or three man crew can easily handle and build. Many designs were tested with double supports to optimize the design strength while still making the supports as lightweight as possible.

Once a successful design was achieved, the design was altered from its original six foot height to determine the maximum height at which the design would still be structurally sound. The design height was increased in one foot increments up to eight feet where the steel framing would no longer resist the blast pressure load. After the maximum height was determined, the polycarbonate thickness was minimized. Table 2.3 below shows the results of the double support design modeling. The highlighted lines are the design that was manufactured and tested against the 15 PSI over 200 milliseconds blast pressure.

Table 2.3. Results from Design Process at 30 and 15 PSI

2 Supports											
Channel	**Support**	**Material**	**Poly Dimensions (in)**		**Spacing (in)**	**Total Deformation Support (in)**	**Total Deformation Poly (in)**	**Total Stress Support (psi)**	**Total Stress Poly (psi)**	**Height (ft)**	**Pressure (psi)**
C10x30	2 - HSS 8x4x0.625	struc steel	3	66x44, 66x38	30, 32	0.58994	1.3073	73789	5621	6	30
C10x30	2 - HSS 8x4x0.625	steel 1006	3	66x44, 66x38	30, 32	0.84884	1.3655	55077	7109	6	30
C10x30	2 - HSS 8x4x0.625	steel 1006	3	78x44, 78x38	30, 32	0.71477	1.2117	53812	6916.3	7	30
C10x30	2 - HSS 8x4x0.625	steel 1006	3	66x44, 66x38	30, 32	0.69669	1.7557	60132	6075.9	8	30
C10x30	2 - HSS 8x4x0.625	steel 1006	1	66x44, 66x38	30, 32	0.36417	1.6443	51158	6493.9	6	30
C10x30	2 - HSS 8x4x0.5	steel 1006	1	66x44, 66x38	30, 32	1.2247	1.9266	72907	13193	6	30
C10x30	2 - HSS 8x4x0.5	steel 1006	1	66x44, 66x38	30, 32	1.1291	1.6948	74223	14569	6	15
C10x30	2 - HSS 8x4x0.625	steel 1006	1	66x44, 66x38	30, 32	0.95851	1.17	57278	7547.2	6	15
C15x33.9	2 - HSS 8x6x0.5	steel 1006	1	65.2x44, 65.2x38	30, 32	2.4978	1.3014	59175	11058	6	15
C10x30	2 - HSS 8x4x0.5	steel 1006	1	78x44, 78x38	30, 32	0.85859	1.6797	59650	8510	7	30
C10x30	2 - HSS 8x4x0.5	steel 1006	1	78x44, 78x38	30, 32	0.99804	1.6453	67200	10940	7	15

2.3 Bolt Design

Once a successful wall design capable of resisting the blast load was achieved, a bolt pattern to fasten the whole design together was designed. The bolt pattern was design based on the shear failure of the bolts.

The bolt design for the polycarbonate safe haven wall was developed using ProEngineer, ANSYS Autodyne Explicit Dynamics, and the American Institute of Steel Construction manual. The design started by developing a model in ANSYS to calculate the required shear force to be resisted by the bolts. The safe haven wall is required to resist a 15 PSI load applied directly to the polycarbonate panels. A 30 PSI load was decided upon to be applied with a dynamic load factor of 2, yielding a total load of 60 PSI and a safety factor of 4. The design was developed in ProEngineer and imported into ANSYS where the loading was applied. The sides of the panel were fixed to simulate the design in an actual field test. Figure 2.12 belows shows how the design looks in ANSYS.

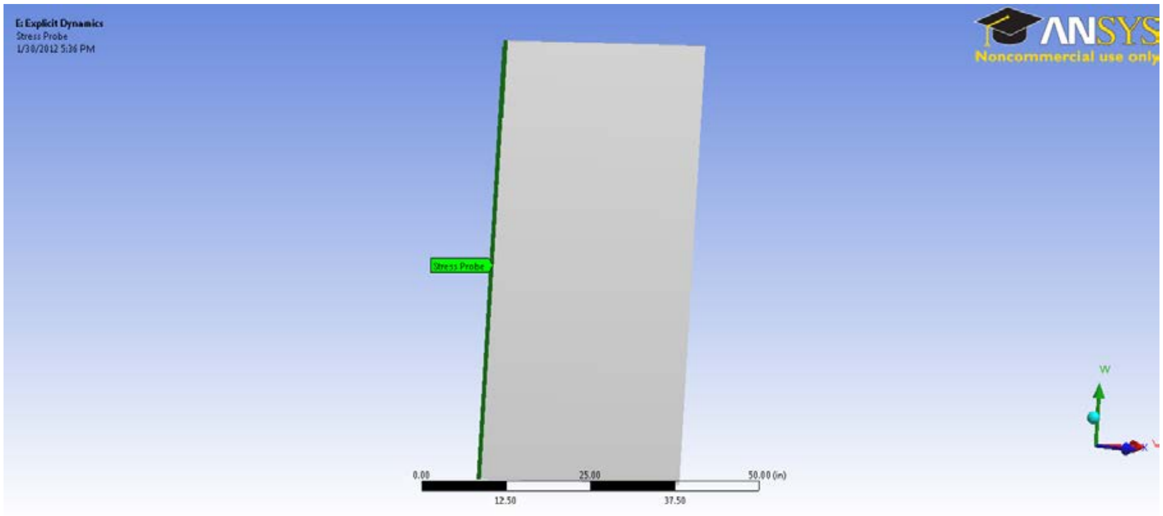
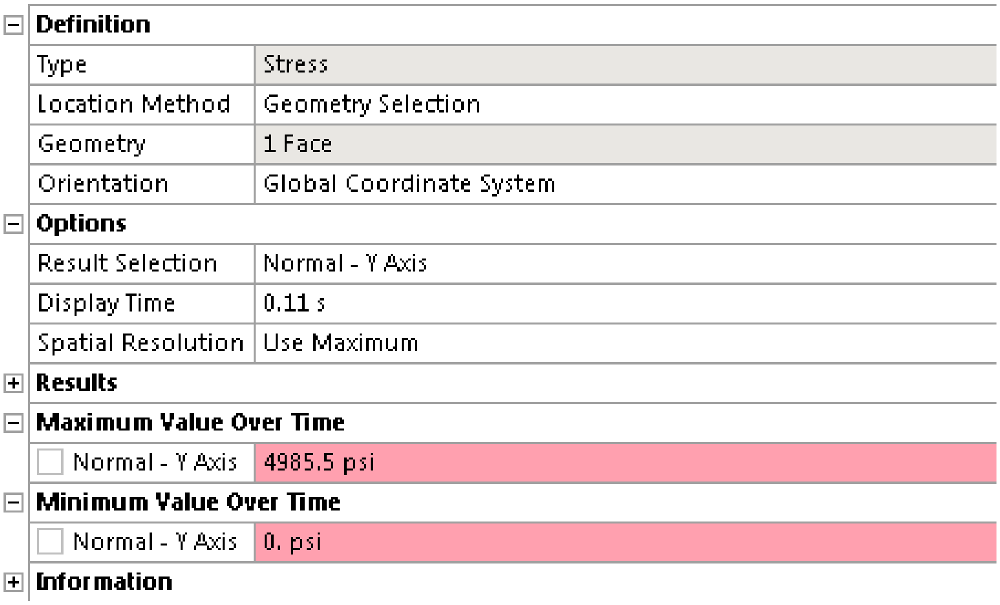


Figure 2.12. Design in ANSYS Used to Provide Shear Stresses in Panel

A stress probe parameter in the model was used to calculate the resulting shear stress of 5000 PSI along the edge of the panel. Figures 2.13 – 2.15 below further illustrate the results from the modeling providing the 5000 PSI shear stress.



⊟ **Definition**

Type	Stress
Location Method	Geometry Selection
Geometry	1 Face
Orientation	Global Coordinate System

⊟ **Options**

Result Selection	Normal - Y Axis
Display Time	0.11 s
Spatial Resolution	Use Maximum

⊞ **Results**

⊟ **Maximum Value Over Time**

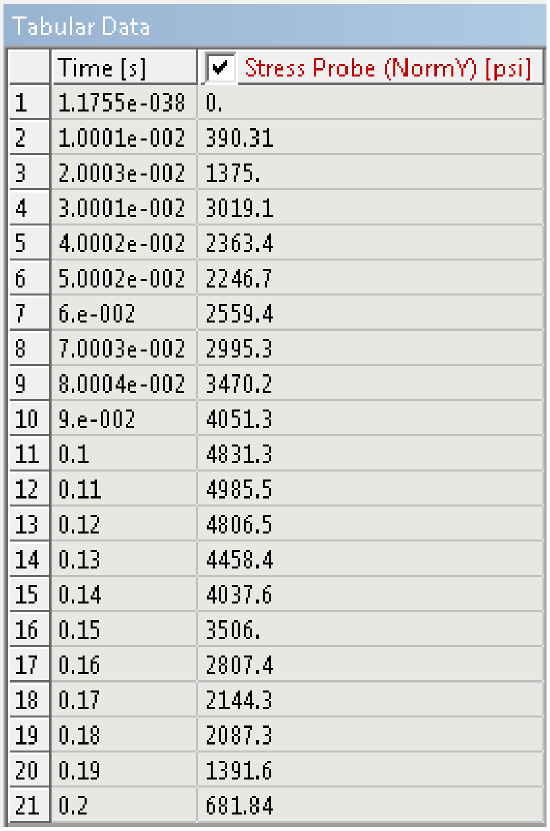
☐ Normal - Y Axis	4985.5 psi

⊟ **Minimum Value Over Time**

☐ Normal - Y Axis	0. psi

⊞ **Information**

Figure 2.13. Details of the Maximum Shear Stress over Time



Tabular Data

	Time [s]	☑ Stress Probe (NormY) [psi]
1	1.1755e-038	0.
2	1.0001e-002	390.31
3	2.0003e-002	1375.
4	3.0001e-002	3019.1
5	4.0002e-002	2363.4
6	5.0002e-002	2246.7
7	6.e-002	2559.4
8	7.0003e-002	2995.3
9	8.0004e-002	3470.2
10	9.e-002	4051.3
11	0.1	4831.3
12	0.11	4985.5
13	0.12	4806.5
14	0.13	4458.4
15	0.14	4037.6
16	0.15	3506.
17	0.16	2807.4
18	0.17	2144.3
19	0.18	2087.3
20	0.19	1391.6
21	0.2	681.84

Figure 2.14. Table of the Shear Stress versus the Model Run Time

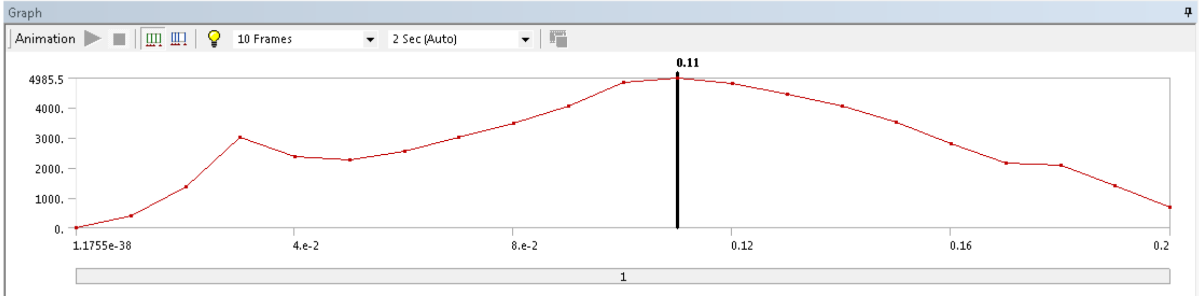


Figure 2.15. Graph of Shear Stress versus Model Run Time

Using the stress value and a known shear strength for a chosen bolt diameter, the total number of bolts required was determined. A total of 22, 11 per edge, 0.75 inch diameter grade 5 bolts were needed to withstand the shear stress generated in each polycarbonate panel. The known shear stress was also used to calculate the nominal shear load used for calculating the shear load each bolt must resist. Since the 5000 PSI stress occurs along the panel edge, the shear load was calculated by multiplying the 1 inch panel thickness and 66 inch height. In turn, the shear load was calculated to be 330,000 lbs. This shear load divided by the number of bolts, 11, gave the required load each bolt must withstand. From here, the actual strength each bolt can resist was calculated using the shear stress of the bolts provided by the Machinery's Handbook 28th edition and the AISC Steel Construction Manual equations. The allowable shear stress of a ¾ inch grade 5 bolt is 60% of its tensile strength which is 120 KSI; therefore, the allowable shear stress is 72 KSI. The allowable shear stress multiplied by the area of one bolt is equal to the load that one bolt can resist. The actual allowable shear stress must be larger than the required shear stress in order for the design to pass. Since the allowable shear stress is greater than the required shear stress, the design is adequate. The calculation for tensile and yield stress for each bolt is the same except for using the tensile and yield stresses given in the handbook. The completed bolt design calculations can be seen in Appendix D.

2.4 Door System Design

With any refuge alternative, passage through the polycarbonate safe haven wall is required and is made possible through a man door that is installed in one of the panels of the wall. The door was constructed of polycarbonate material as well. The door was designed to withstand the 15 PSI curve prescribed by MSHA. This design was tested in the University of Kentucky Explosives Research Team (UKERT) shock tube and will be discussed in Chapter 3. The man door was designed to have a 30 inch opening to allow passage by miners into the safe haven.

For the door design, HAZL was used for initial designs and prototyping. The code is limited distribution through the Army Corps of Engineers Protective Design Center. “HAZL performs a single degree of freedom (SDOF) analysis to calculate the glazing response to a blast loading and a debris transport model for predicting fragment trajectory. The program allows modeling of monolithic glass or plastic windows, laminated windows, insulated glass units and windows retrofitted with anti-shatter film. The user inputs the window geometry, glazing type, material and thickness, and blast load. The blast load can be input manually, read from an input file, or generated for a given charge weight and standoff distance. Output includes the hazard level, glazing response parameters, reaction loads, and required frame bite. Results can be displayed either in a text format or as graphical plots. The program can also produce pressure-impulse (P-i) curves for the specified window to be used in vulnerability and security planning analyses.” (HAZL, 2013)

Based on previous experience testing fenestration systems with polycarbonate material, two thicknesses (0.75 inch and 1 inch) were calculated using HAZL to determine the thickness necessary for the door material. Each thickness was calculated using a door size of 30 inches by 30 inches. This design assumption should hold true even though the door assembly is rounded. The maximum span of the circular opening is 30 inches. The first thickness evaluated was 0.75 inches. For initial consideration a PI curve was generated for the 0.75 inch thick material. Figure 2.16 shows the PI curve for the 0.75 inch door. The lower asymptote of the curve approaches 15 PSI.

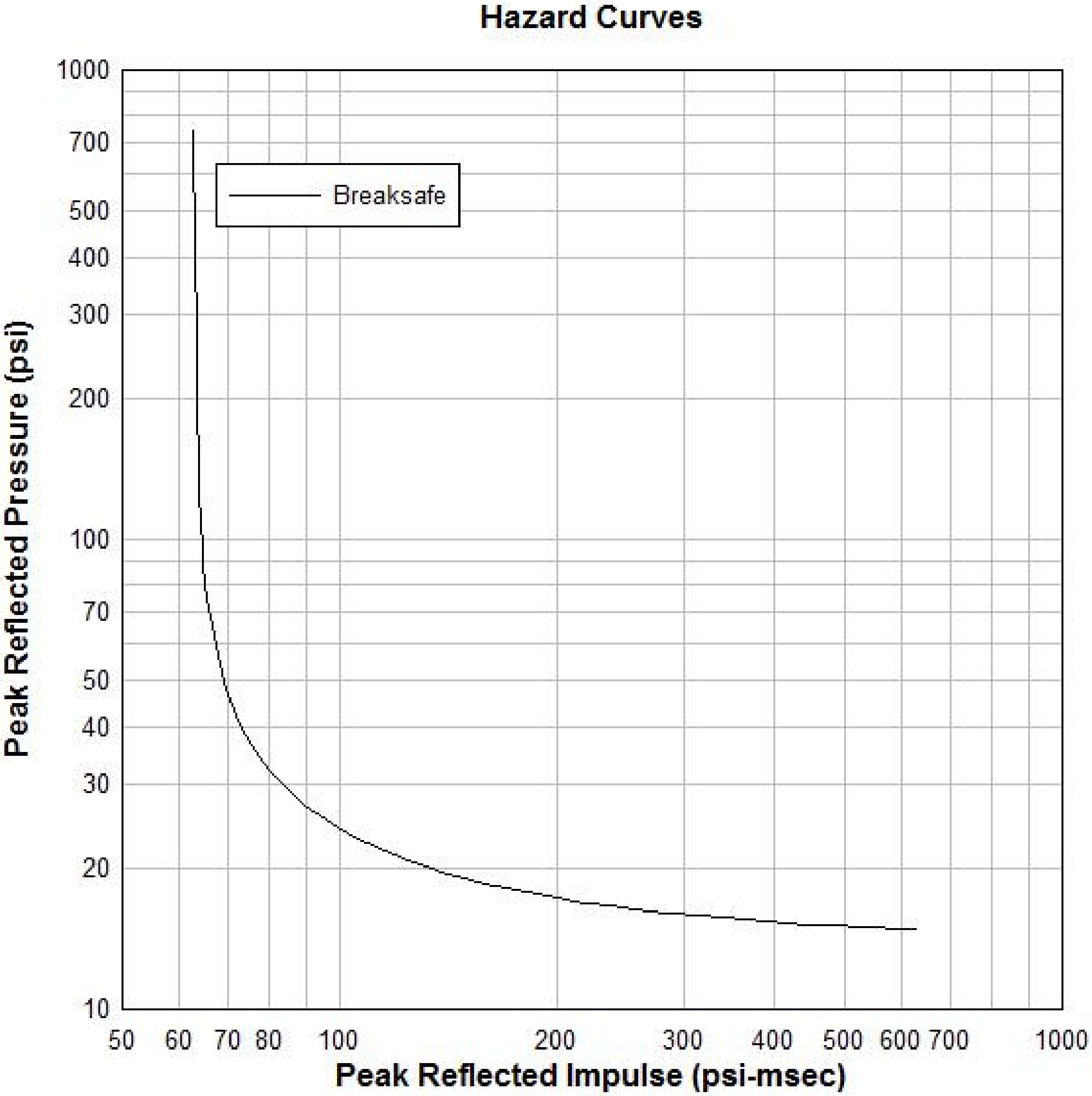


Figure 2.16. PI Curve for 0.75 Inch Thick Polycarbonate Door

Further analysis using the functions of HAZL was necessary to determine the performance of the door under the loading described by the MSHA 15 PSI curve. A CSV file was generated for use in the HAZL code for analysis. Output from the model predicted that the “glass does not crack and is retained in frame.” The required bite for this condition is 0.887 inches which is satisfied by the door overlap which is approximately 2 inches. The design also resulted in a maximum effective static capacity of 39.96 PSI. Based on the results of the HAZL analysis, 0.75 inches is sufficient for material thickness of the door system. Complete output from the HAZL program can be found in Appendix A.

HAZL was also used to calculate the performance of 1 inch polycarbonate material for the door system. Figure 2.17 shows the PI curve for 1 inch polycarbonate material subjected to the MSHA design curve. For the 1 inch thickness the asymptote approaches 25 PSI.

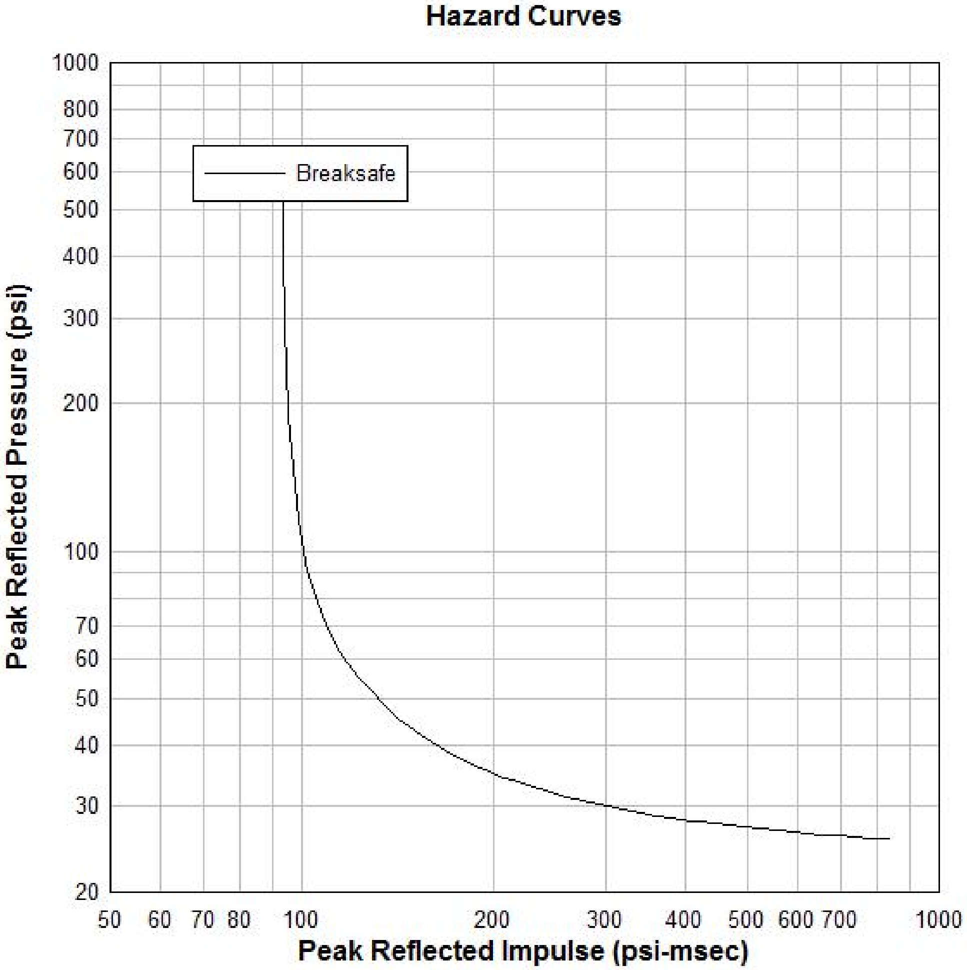


Figure 2.17. PI Curve for 1 Inch Thick Polycarbonate Door

Utilizing the same MSHA CSV file, further analysis was performed using HAZL for the 1 inch material. The output predicted the same performance where the "glass does not crack and is retained in the frame." The maximum effective static capacity according to HAZL for the 1 inch polycarbonate is 64.84 PSI with a recommended minimum bite of 0.852 inches. Complete HAZL output for the 1 inch material can be found in Appendix B.

HAZL calculations show that either thickness is acceptable for use in the door system. At first glance, the 1 inch material provides a better safety factor than the 0.75 inch material. Previous testing experience has shown that HAZL will underestimate the resistance of polycarbonate material; thus 0.75 inch material was selected for testing.

One additional HAZL calculation was performed incorporating the 0.75 inch material and the actual tested wave form from the UKERT shock tube which will be discussed in chapter 3. Another CSV file was produced based on actual data taken from the test. The model predicted a no break condition where the glass does not crack. The model also predicted a maximum deflection of 2.08 inches. This corresponds well to the measured deflection of the panels reported in Table 3.2 which had a max deflection of approximately 2 inches at 15 PSI. Confirmation of the model provides confidence in the design thickness of 0.75 inches. Complete output from the HAZL model for the 0.75 inch thick door subjected to the test load can be found in Appendix C.

Latch and hinge components were tested rather than evaluated through calculations due to the complexity of the system and difficulty of accurately modeling their response. Through the combination of design calculations and testing, the polycarbonate door system was validated for performance as a 15 PSI safe have door.

2.5 Model for Underground Coal Mine Environment Using FLAC3D

While investigating a way to physically test the system with explosives, a model for use in an underground coal mine environment using FLAC3D was developed. FLAC3D is a numerical modeling code for advanced geotechnical analysis of soil, rock, and structural support in three dimensions. It utilizes an explicit finite difference formulation that can model complex behaviors not readily suited to finite element modeling codes (FLAC3D, 2013). FLAC3D allows the user to input all the parameters for analysis and determine desired course of evaluation through input codes.

The first step in modeling the polycarbonate wall for an underground coal mine environment was to determine a suitable underground coal mine willing to support the projects goals. With a mine site selected, core hole data from the mine was gathered in order to determine the depths and thicknesses of stratums for modeling. Next, the dimensions of the model base had to be selected very carefully to allow for adequate modeling of the underground environment and timely conversion of the model. Multiple model base configurations were conducted before achieving the optimal parameters. The optimum model design layout comprised of a two entry section with one crosscut where the polycarbonate wall would be placed. However, to allow for faster conversion of the model, the layout was reduced to include only half of the pillars thus allowing for symmetry. Figures 2.18 and 2.19 provide drawings of the final layout used in the FLAC3D model.

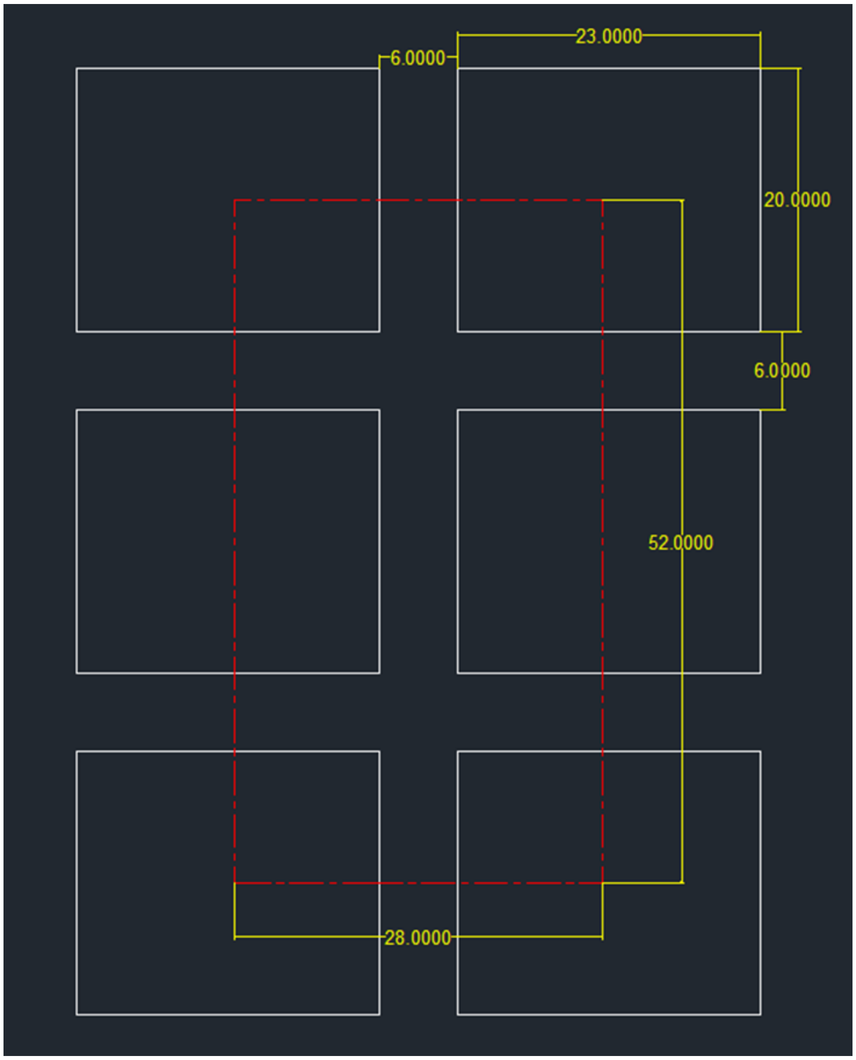


Figure 2.18. Two Entry, One Crosscut Proposed FLAC3D Model (dimensions in meters)

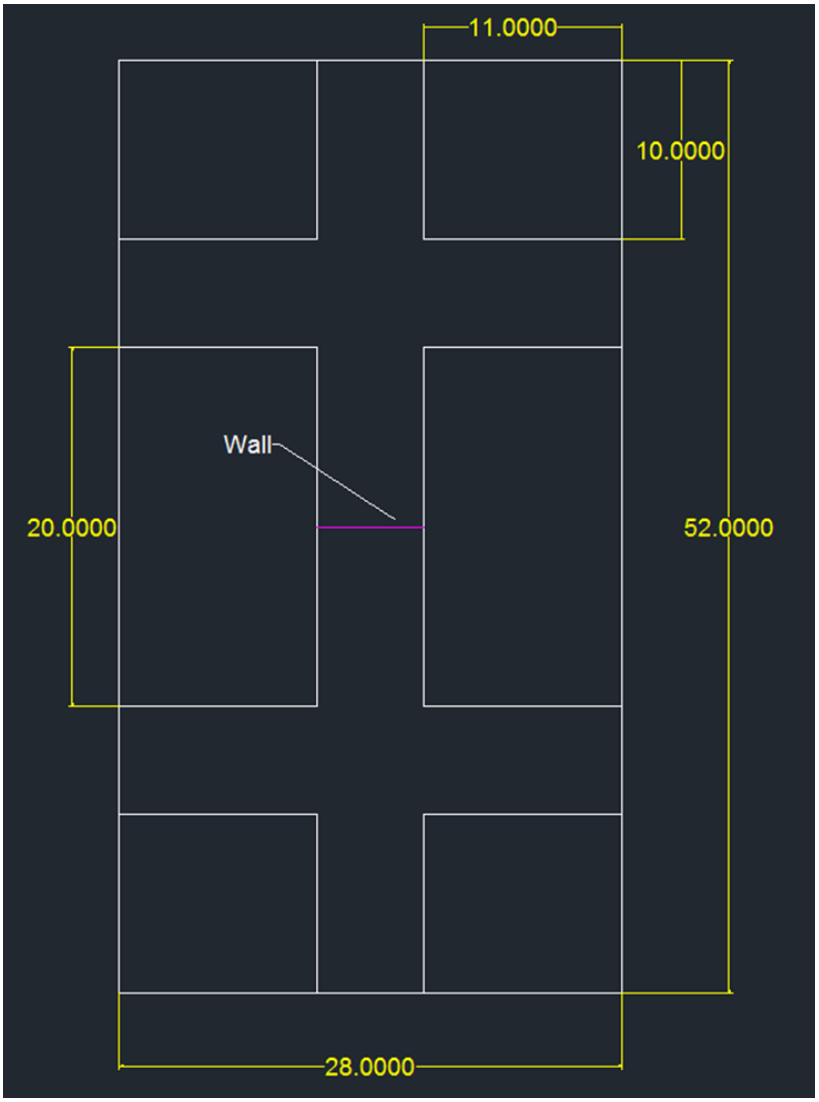


Figure 2.19. Final FLAC3D Model Setup (dimensions in meters)

The model consisted of five layers, a gray sandstone and dark gray shale above and below a coal seam. For modeling purposes, stratums lying above and below the modeled area were allocated differently. The remaining stratums below the modeled area are deemed irrelevant while the remaining stratums above the modeled area will be realized by applying a 1.79e6 Pascal (~260 PSI) vertical stress to the top of the model to represent the overburden. With the model base dimensions and layers established, required model parameters were coded to create the base model and allow for conversion.

Table 2.4 below provides the dimensions for each stratum along with the values used for the required modeling parameters.

Table 2.4. Strata Parameters Used for FLAC3D Modeling

Strata Parameters														
	x	y	z		E		v	Density		Tensile		ϕ	Cohesion	
Overburden														
Gray sandstone	170.6	91.84	9.84	ft	2800000	psi	0.18	165	lb/ft3	4833	psi	37	3916	psi
	52	28	3	m	1.90E+10	Pa		2640	kg/m3	3.33E+07	Pa		2.70E+07	Pa
zones	52	28	3											
Dark Gray Shale	170.6	91.84	9.84	ft	1740000	psi	0.27	150	lb/ft3	950	psi	30	5511	psi
	52	28	3	m	1.20E+10	Pa		2400	kg/m3	6.55E+06	Pa		3.80E+07	Pa
zones	104	56	15											
Coal														
Coal	170.6	91.84	6.56	ft	666000	psi	0.38	80	lb/ft3	962	psi	28	325	psi
	52	28	2	m	4.60E+09	Pa		1280	kg/m3	6.63E+06	Pa		2.24E+06	Pa
zones	104	56	10											
Floor														
Dark Gray Shale	170.6	91.84	9.84	ft	1130250	psi	0.27	150	lb/ft3	870	psi	30	5511	psi
	52	28	3	m	7.80E+09	Pa		2400	kg/m3	5.99E+06	Pa		3.80E+07	Pa
zones	104	56	15											
Gray Sandstone	170.6	91.84	6.56	ft	2650000	psi	0.18	165	lb/ft3	4833	psi	37	3916	psi
	52	28	2	m	1.80E+10	Pa		2640	kg/m3	3.33E+07	Pa		2.70E+07	Pa
zones	52	28	2											

Once the base of the model converged, excavation and bolting of the entries and crosscuts took place. Both the entries and crosscuts are six meters wide (~20 feet). For roof support, five three meter long bolts were installed on one meter centers throughout the excavation for roof support. Upon completion of the excavation and bolt installation, the model was again allowed to converge to tabulate stresses in the bolts due to gravity. Table 2.5 provides the properties used for the bolts and Figures 2.20 – 2.23 show the completed excavation with bolts installed and stresses in the bolts.

Table 2.5. Bolt Properties Used in FLAC3D

Bolt Properties				
Area	0.0085	m²	0.0914	ft²
Youngs Modulus	2.00E+11	Pa	2.90E+07	psi
Tensile Yield Strength	1.00E+10	N	2.20E+09	lb
Grout Stiffness	7.00E+06	Pa	1015	psi
Grout Cohesive Strength	100	N/m	6.85	lb/ft
Grout Friction Angle	30	degrees	30	degrees
Grout Exposed Perimeter	0.16	m	0.5248	ft

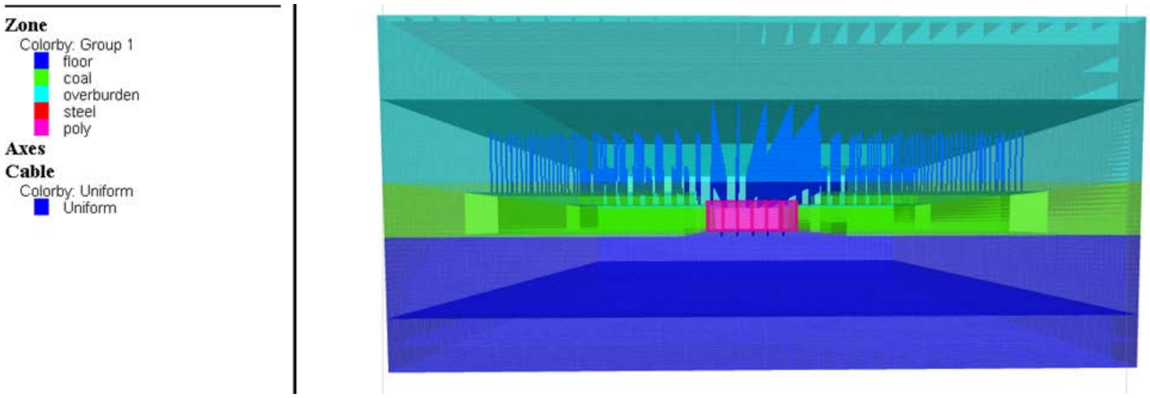


Figure 2.20. Plot of Completed Model, Zones Depicted by Different Colors

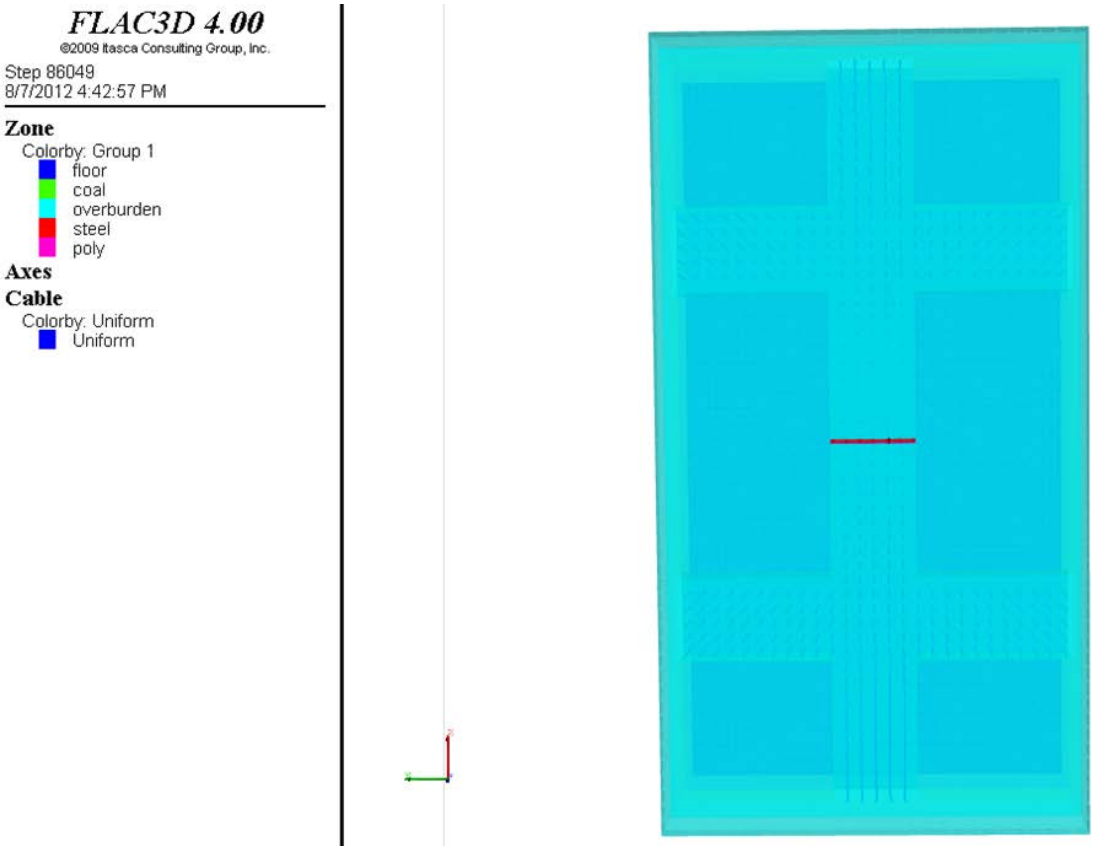


Figure 2.21. Top View of Completed Model

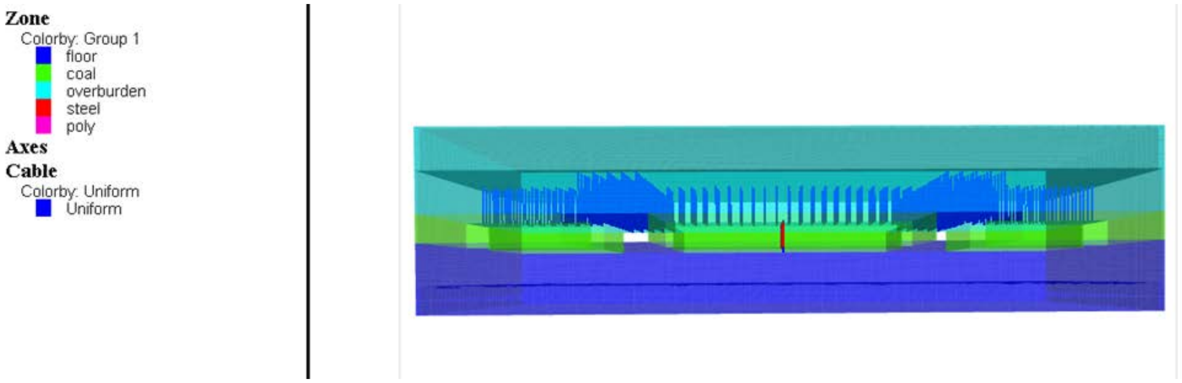


Figure 2.22. Side View of Completed Model

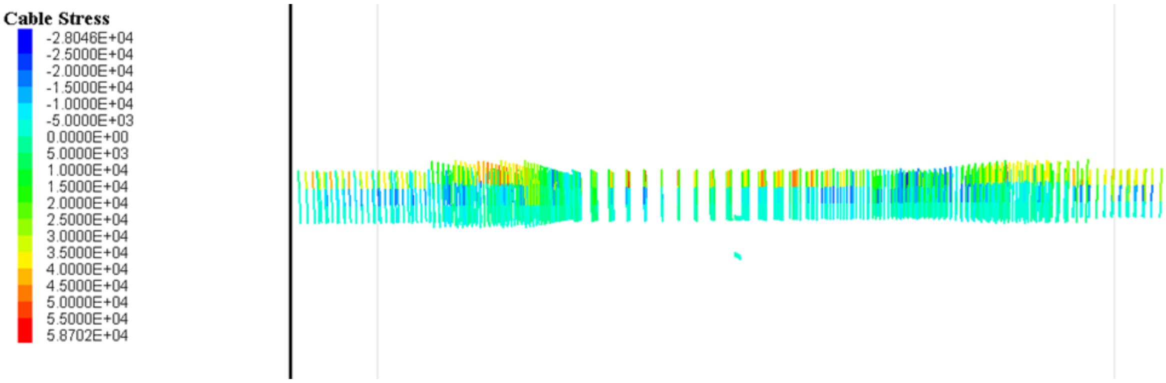


Figure 2.23. Plot of the Stress in the Bolts

With the model to the current state of equilibrium, the polycarbonate wall system was placed in the crosscut as shown in previous figures. The polycarbonate wall was anchored to the floor and ceiling with 0.3 meter bolts in anticipation of similar bolts being readily available for the underground installation. These bolts have the same parameters as the bolts used before during the excavation stage of the modeling. All of the dimensions of the wall are the same as the successful design in the earlier section of this report. The parameters of the steel and polycarbonate used for the wall in the model can be seen in Table 2.6.

Table 2.6. Polycarbonate Wall Parameters Used In FLAC3D

Polycarbonate Wall Parameters				
E		v	Density	
Steel				
29007547	psi	0.3	490	lb/ft³
2.00E+11	Pa		7850	kg/m³
Polycarbonate				
310380	psi	0.37	75	lb/ft³
2.14E+09	Pa		1200	kg/m³

The final step in the modeling process was to apply the prescribed blast pressure to the polycarbonate wall system. A 206,843 Pascal (30 PSI) pressure was applied to the wall and the model was allowed to converge for the final time. By applying pressure to the wall, results were tabulated for stresses and deflections in the polycarbonate wall. Figures 2.24– 2.33 show the front and back view of the stresses and deflections that were developed in the polycarbonate wall from the applied pressure and gravitational forces of the model.

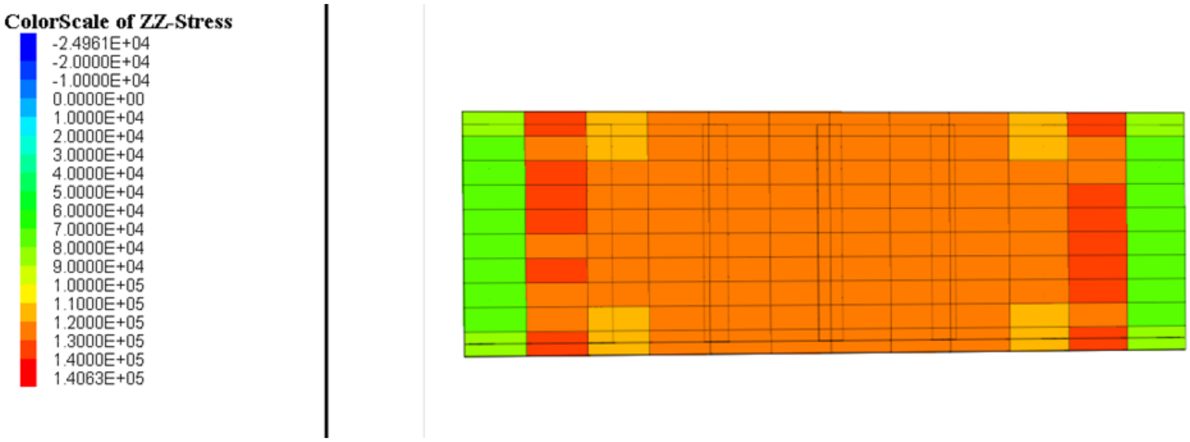


Figure 2.24. Front View of the ZZ-Stress in the Polycarbonate Wall

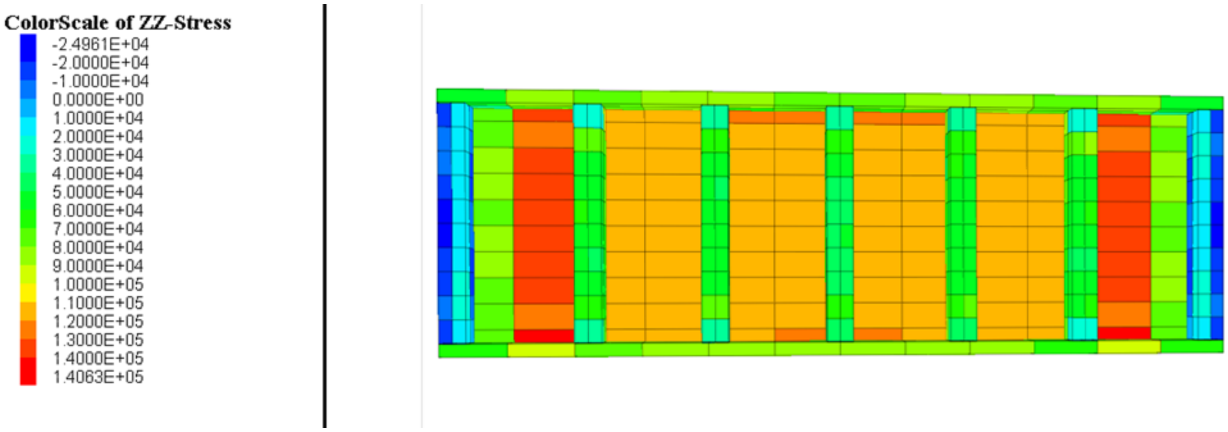


Figure 2.25. Back View of the ZZ-Stress in the Polycarbonate Wall

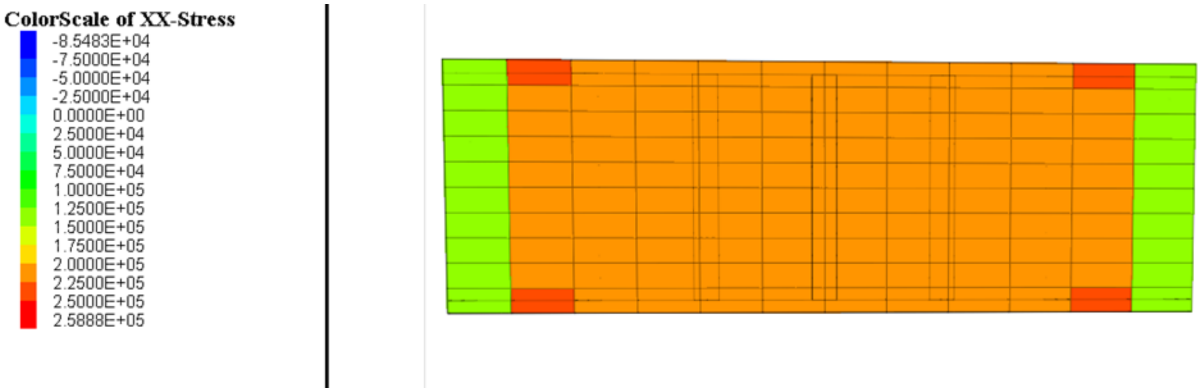


Figure 2.26. Front View of the XX-Stress in the Polycarbonate Wall

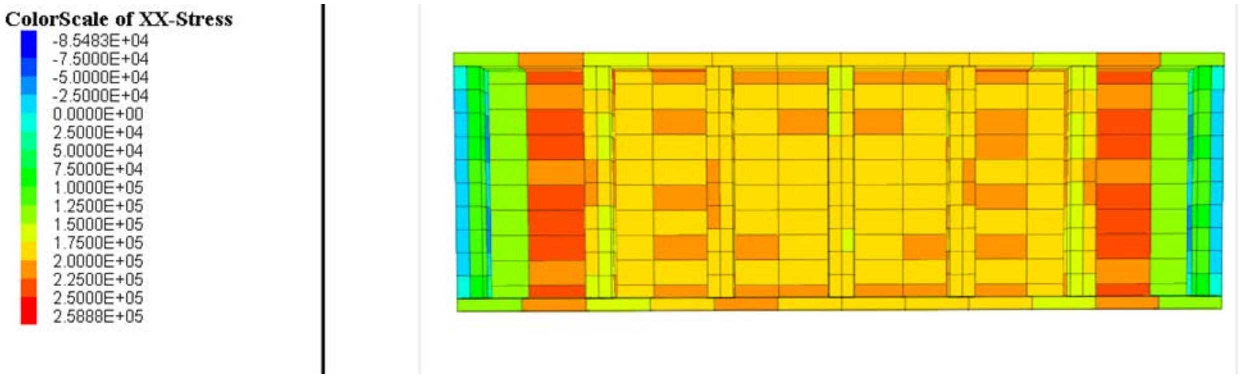


Figure 2.27. Back View of the XX-Stress in the Polycarbonate Wall

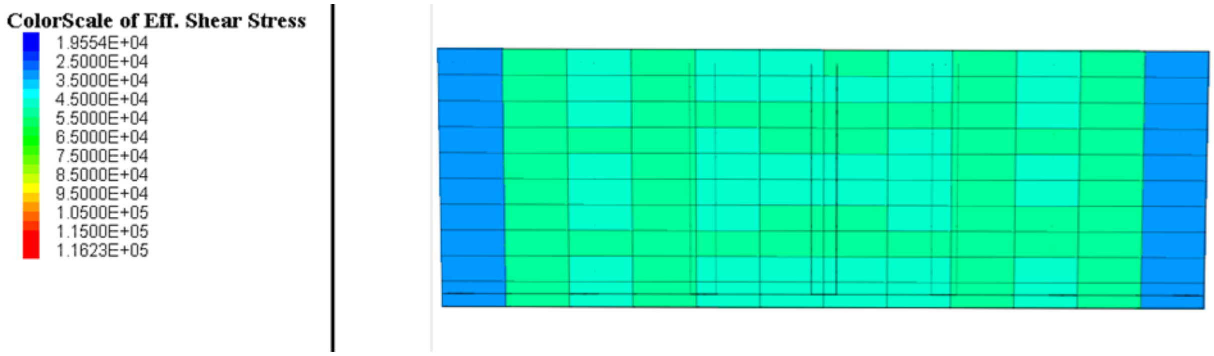


Figure 2.28. Front View of the Shear Stress in the Polycarbonate Wall

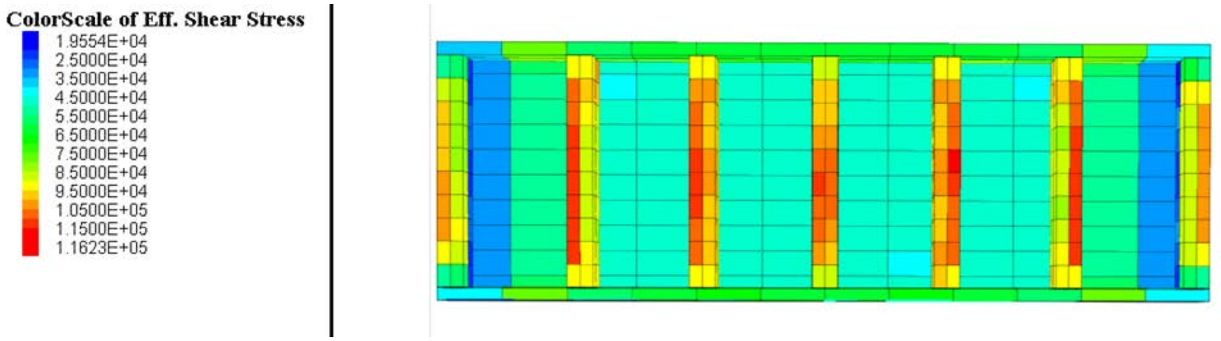


Figure 2.29. Back View of the Shear Stress in the Polycarbonate Wall

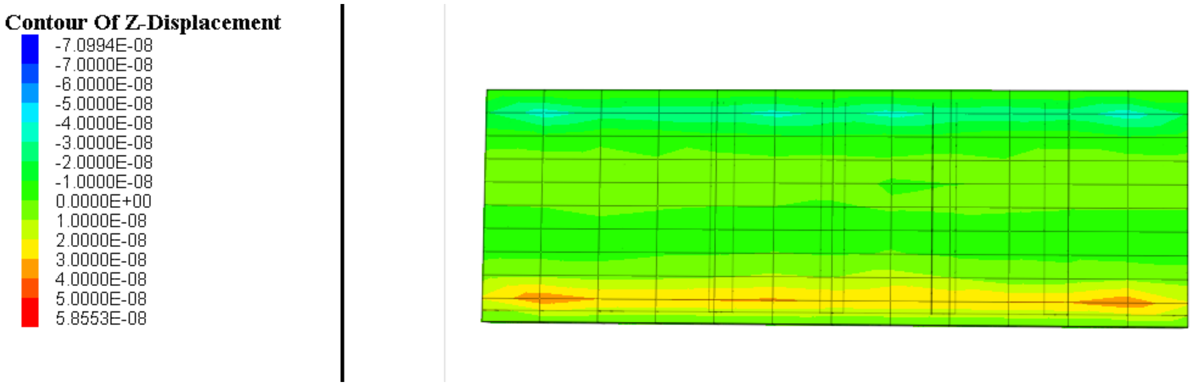


Figure 2.30. Front View of the Contour of Z-Displacement of the Polycarbonate Wall

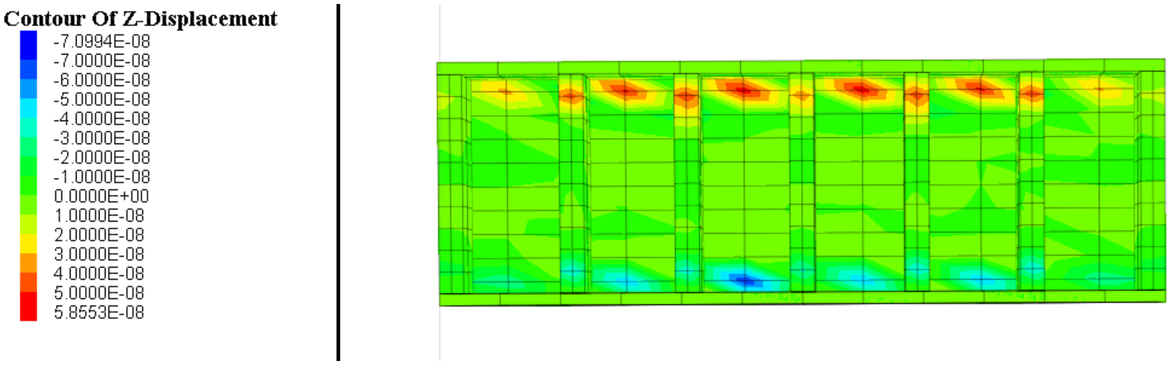


Figure 2.31. Back View of the Contour of Z-Displacement of the Polycarbonate Wall

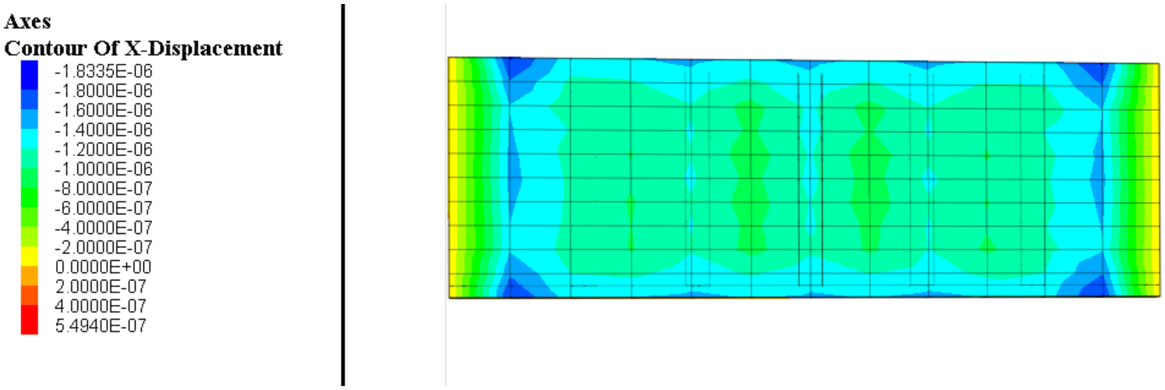


Figure 2.32. Front View of the Contour of X-Displacement of the Polycarbonate Wall

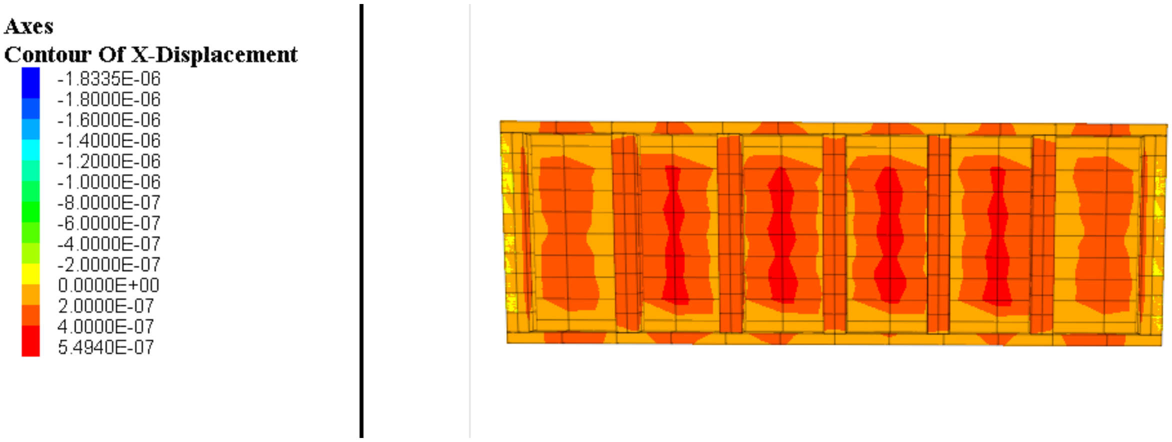


Figure 2.33. Back View of the Contour of X-Displacement of the Polycarbonate Wall

The stresses and displacements of the stratums throughout the modeling process were also calculated and can be seen in Figures 2.34 – 2.37. Finally, Table 2.7 contains all of the maximum values for each calculated parameter during the modeling process.

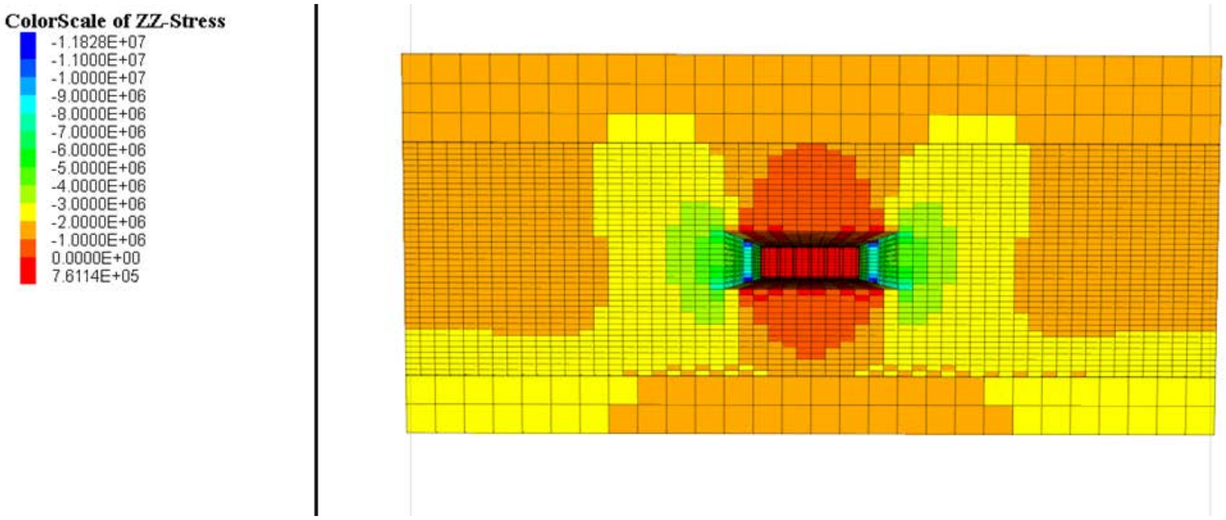


Figure 2.34. Plot of the Contour of ZZ-Stress in the Ground

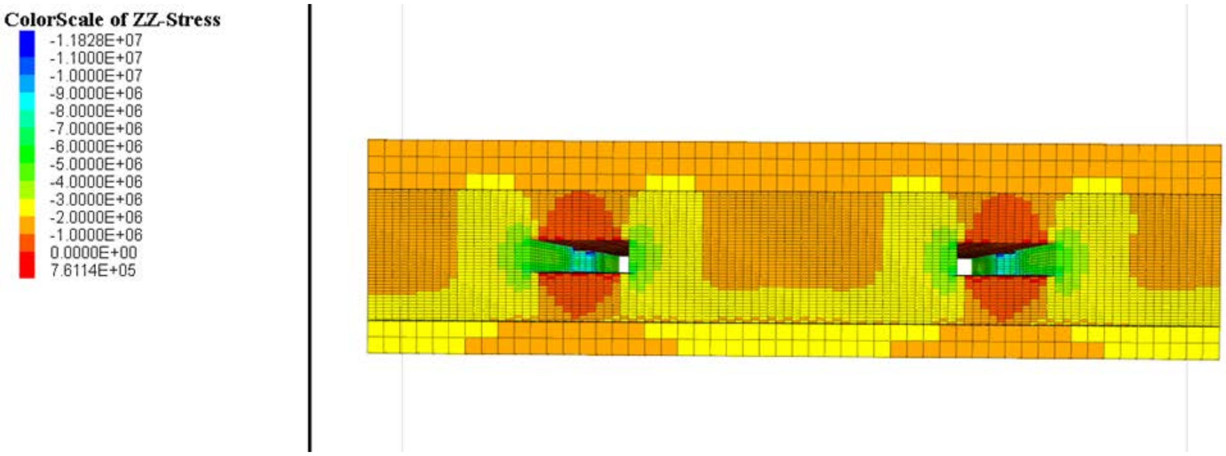


Figure 2.35. Plot of the Contour of ZZ-Stress in the Ground

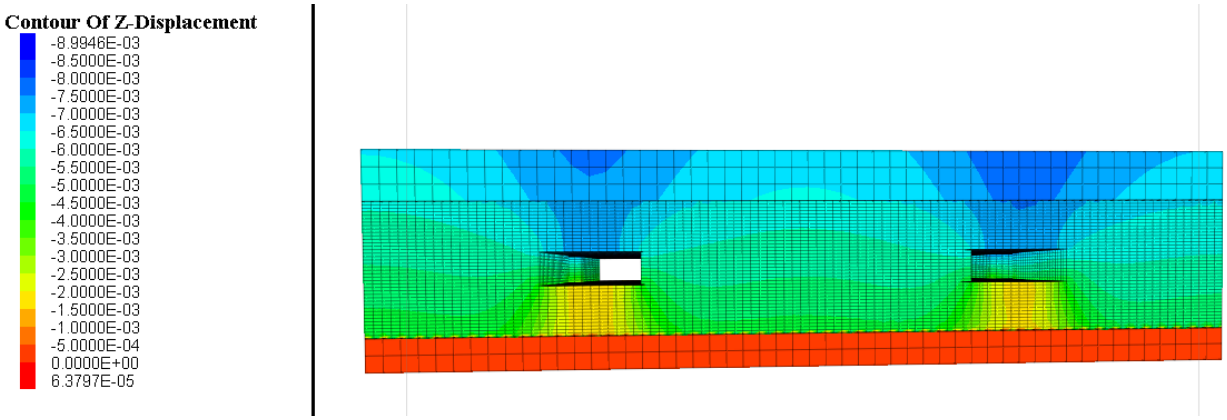


Figure 2.36. Plot of the Contour of Z-Displacement of the Ground

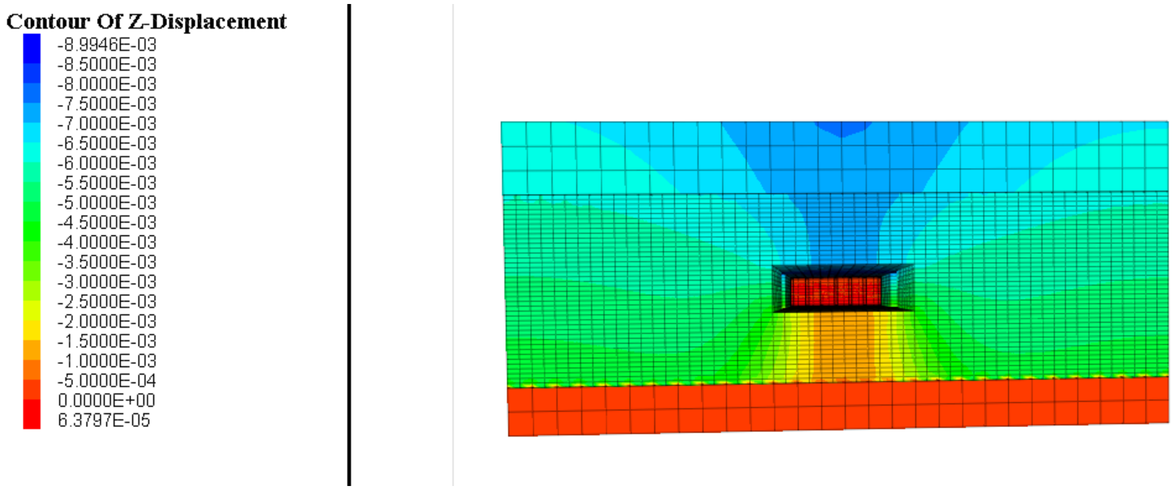


Figure 2.37. Plot of the Contour of Z-Displacement of the Ground

Table 2.7. FLAC3D Model Results

FLAC3D MODEL RESULTS		
	Max	
Bolts		
Stress	58702	Pa
Figure 2.23	8.51	PSI
Polycarbonate Wall		
ZZ-Stress	140630	Pa
Figurs 2.24 - 2.25	20.4	PSI
XX-Stress	258880	Pa
Figures 2.26 - 2.27	37.55	PSI
Shear Stress	116230	Pa
Figures 2.28 - 2.29	17	PSI
Z-Displacement	-0.00000008	meter
Figures 2.30 - 2.31	-0.0000031	inch
X-Displacement	0.0000005	meter
Figures 2.32 - 2.33	0.000022	inch
Ground		
ZZ-Stress	-11828000	Pa
Figures 2.34 - 2.35	-1715.51	PSI
Z-Displacement	-0.00899	meter
Figures 2.36 - 2.37	-0.354	inch

The results from the FLAC3D modeling are very good with none of the maximum values being larger than allowed by material properties. The acceptable modeling results allowed the project to move forward with greater confidence and begin underground construction of the polycarbonate wall.

CHAPTER 3. POLYCARBONATE WALL CONSTRUCITON AND TESTING

3.1 Introduction

The construction and testing of the polycarbonate safe haven wall design at the University of Kentucky Explosives Research Team's (UKERT) high explosive shock tube facility in Georgetown, Kentucky will be analyzed in this chapter. Construction and testing was performed for two different sized walls along with the door system to properly analyze the design. The physical explosive testing results will be used to measure pressure and deflection of the safe haven wall and the deflections will be compared to the ANSYS finite element modeling for model validation.

3.2 Full Scale Polycarbonate Wall Testing

3.2.1 Full Scale Polycarbonate Wall Construction

The construction process started with reducing the cross-sectional area of the existing 10 foot x 10 foot shock tube opening down to six foot high by 114 inches wide to simulate a six foot entry in a coal mine and keep explosive pressure from easily escaping the opening. 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 3.5 x 12 x 120 inch oak boards on top of an I-beam support as shown in Figure 3.1.

Figure 3.1. I-beam and Oak Boards Size Adjustment Configuration

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 as shown in Figure 3.2. The I-beam was also supported vertically by oak boards on each end.

Figure 3.2. I-beam Horizontally Bolted Through Oak Boards to Steel Shock Tube Frame with Steel Angle

Once the I-beam and oak board size adjustment was in place, 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. Figure 3.3 shows the completed size adjustment with threaded steel bars inserted to anchor the system together.

Figure 3.3. 5/8 inch Threaded Steel Bars Through Boards and I-beam

With the shock tube opening to the required dimensions for the polycarbonate wall system, the steel frame was brought in to place and installed. The steel frame was drilled and assembled off-site to assure the steel and bolt holes would all align. Figures 3.4, 3.5, 3.6, and 3.7 show the installation progression. As with the models, the sides of the wall system remained free to force a one way reaction.

Figure 3.4. Steel Framing Assembled Off-Site

Figure 3.5. Steel Framing Final Placement for Bolting

Figure 3.6. Steel Framing Bolted in Place

Figure 3.7. Bolt Pattern on Bottom Channel of Steel Frame

Following the installation of the steel framing, one inch polycarbonate panels were cut to the required 66 x 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 was on the outside of the system. Figures 3.8, 3.9, and 3.10 show the installation progression of the polycarbonate panels.

Figure 3.8. Middle Polycarbonate Panel Installation

Figure 3.9. Bolt Hole Drilled in Polycarbonate Panel

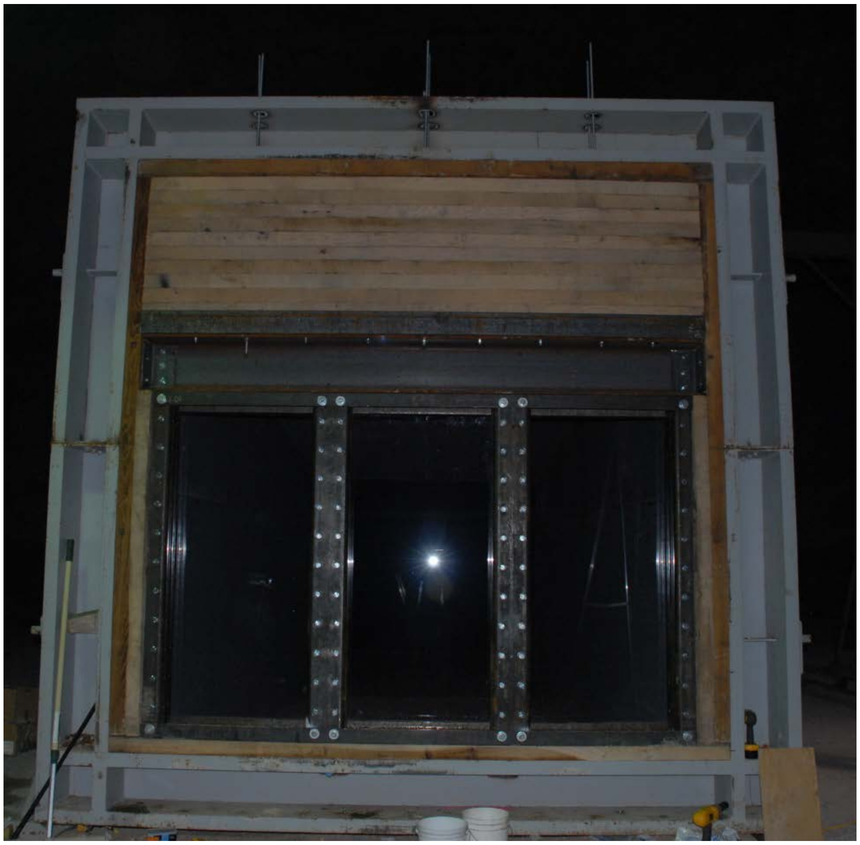


Figure 3.10. All Polycarbonate Panels Installed

The final step in the construction of the polycarbonate wall system was placing steel plates on the perimeter of the oak board size adjustments to add extra support against their movement and to further help seal off any opening where explosive pressure may be lost. The 0.25 inch thick steel plates were simply drilled and fastened to the oak boards using 2.25 inch long, 0.25 inch diameter anchors. With the steel plates in place, the wall installation was complete and ready for testing. The steel plate's placement can be seen in Figures 3.11, 3.12, and 3.13.

Figure 3.11. Steel Plate Placement on Inby Side of System

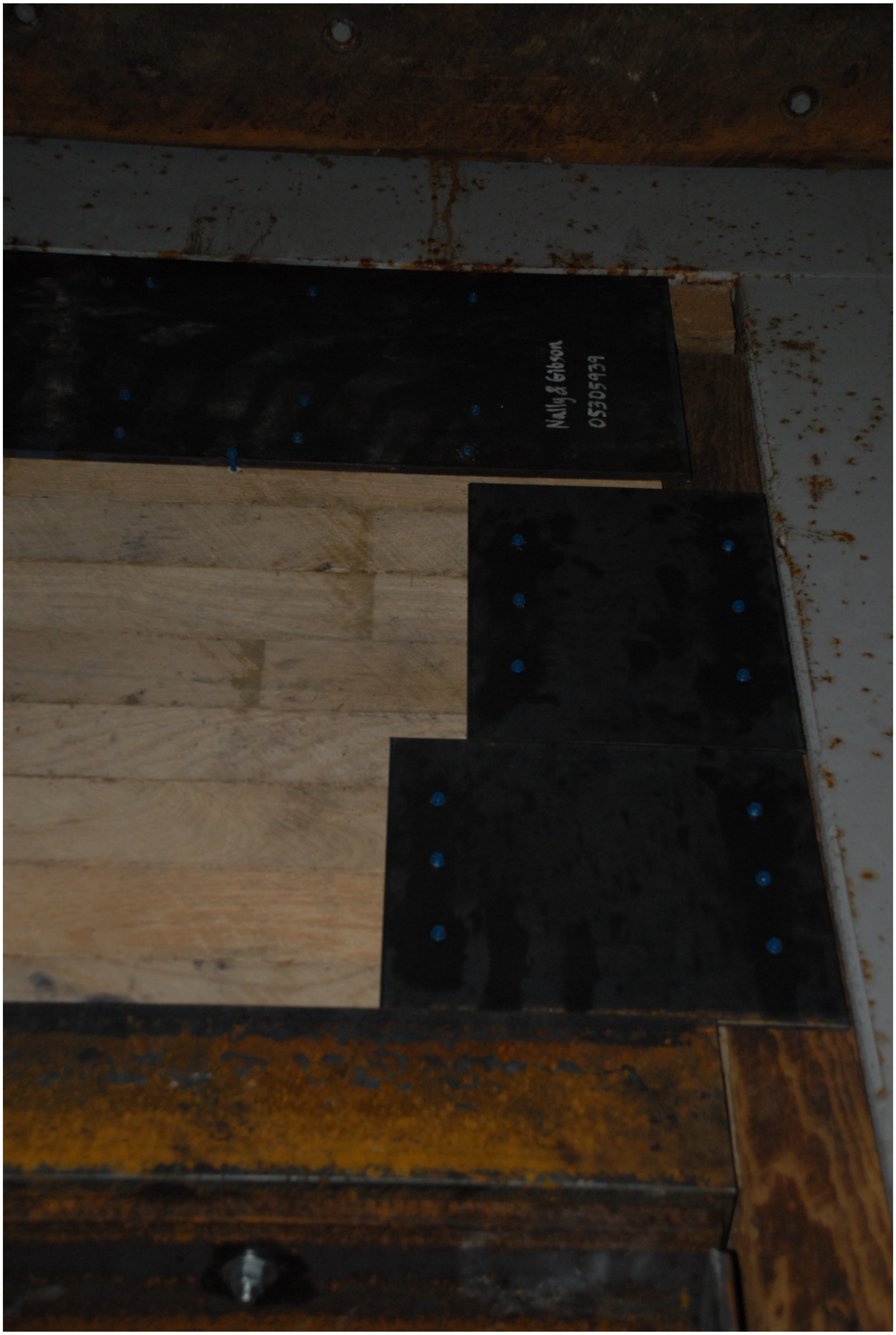


Figure 3.12. Steel Plate Placement

Figure 3.13. Steel Plate Placement on Outby Side of System

3.2.2 Full Scale Polycarbonate Wall Testing

With the polycarbonate safe haven wall installed, the next step was to test system. The testing setup consisted of three reflected pressure sensors located as shown in Figure 3.14 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, 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. Figure 3.15 shows one frame from a high speed video along with the laser being used to measure deflection. The pressure for each test was created by hanging a C4 charge 51 feet from the wall. This initial round of testing consisted of four tests.

Figure 3.14. Pressure Sensor Locations for Testing

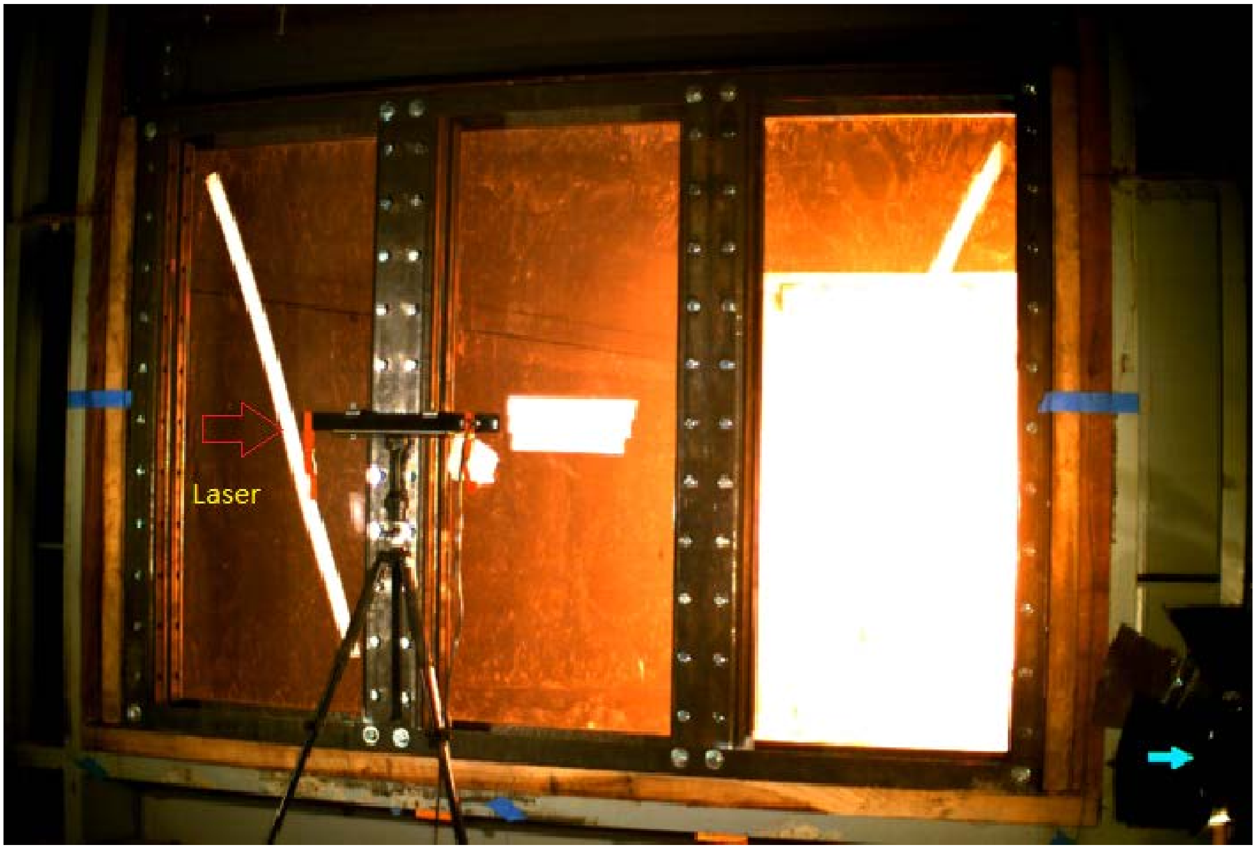


Figure 3.15. High Speed Video Screen Shot and Displacement Laser

3.2.3 Full 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 3.1.

Table 3.1. Deflection Results from Model and Actual Test

Test Number	ANSYS Deflection (in)	Testing Deflection (in)	Average Pressure (psi)	Average Impulse (psi-ms)	Laser Location
*03161202	1.22	0.907485	7.61	70.41	Center of middle polycarbonate panel
*03161203	0.33354	0.73311	7.6	69.73	Center of left-center vertical support
*03161204	0.5075	0.906855	7.69	71.57	Center of far left vertical support
*03161205	1.9512	1.03918	7.61	69.11	Center of left polycarbonate panel

From the results in Table 3.1, the ANSYS deflections vary from as little as 0.33 inches to 1.95 inches with the actual testing deflections varying from 0.73 inches to 1.04 inches. The deflections from the model were greater on the polycarbonate panel and less on the vertical steel supports. The deflection comparisons between the blast testing and the ANSYS model were performed using the deflection laser data and the displacements found by importing the pressures created 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 3.1 above. The deflection comparisons can be seen in Figures 3.16 – 3.19. The curves comparing the deflection of the polycarbonate material in Figures 3.16 and 3.19 match quite well with the exception of the deflections being higher in the ANSYS models. 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. However, information has been obtained by the manufacturer and a material model is currently under development but was not able to be completed by the end of the research. 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.

The deflection comparison of the curves in Figure 3.17 and 3.18 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. 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 steel is much more when compared to the fixed 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.

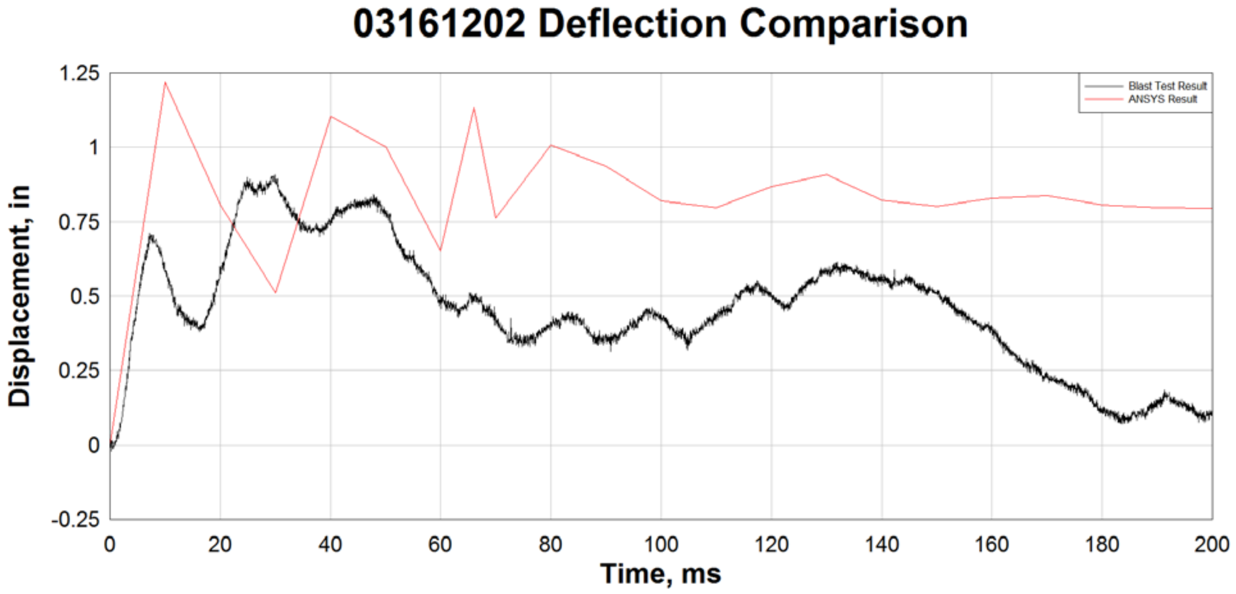


Figure 3.16. Test 03161202 Displacement Comparison of Center Polycarbonate Panel

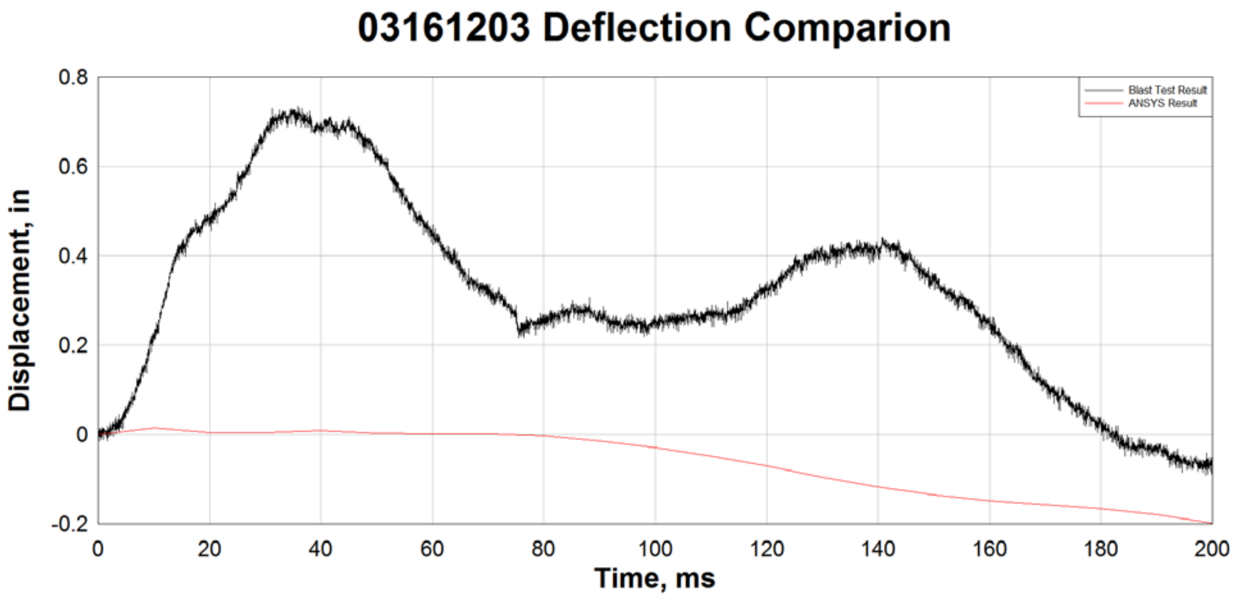


Figure 3.17. Test 03161203 Deflection Comparison of Left-Center Vertical Upright

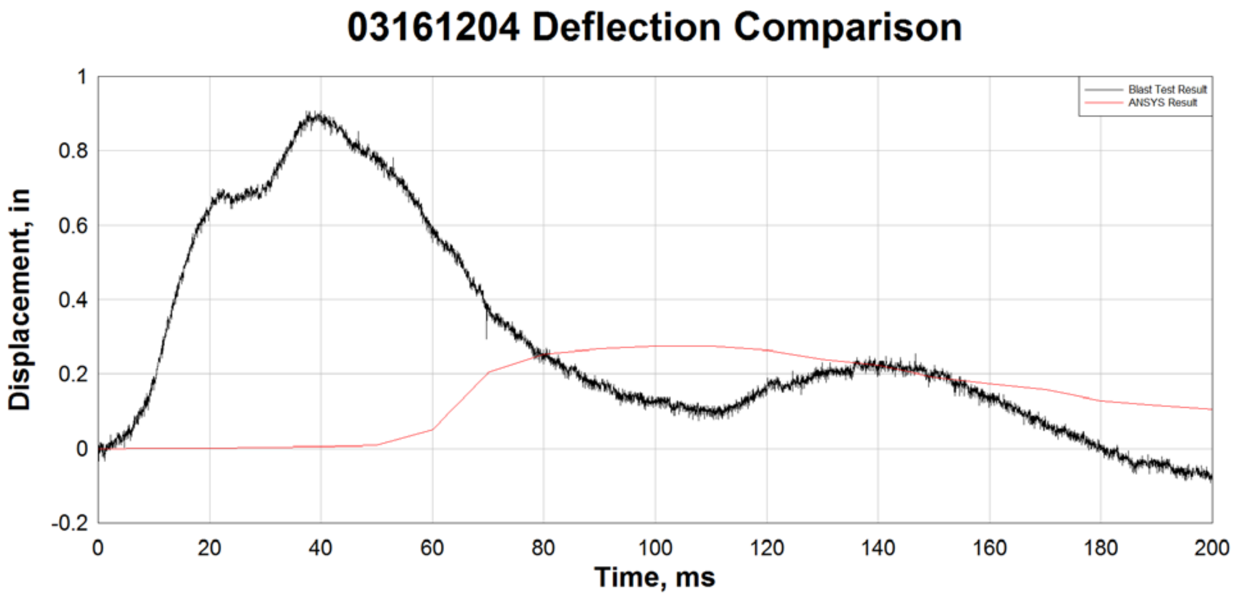


Figure 3.18. Test 03161204 Deflection Comparison of Far Left Vertical Upright

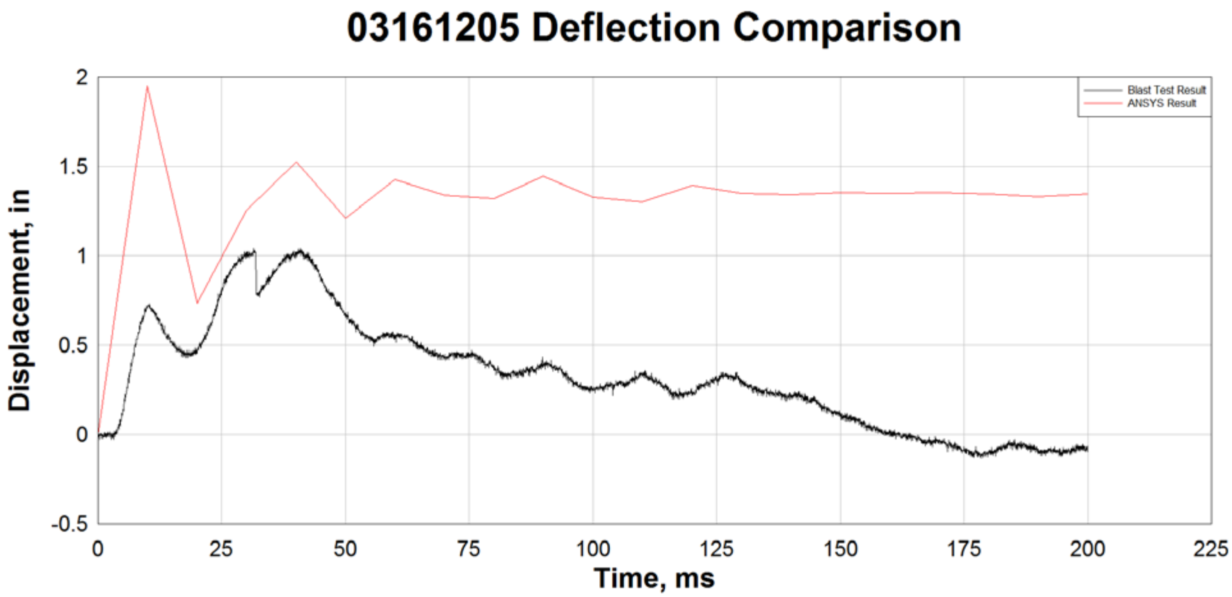


Figure 3.19. Test 03161205 Deflection Comparison of Left Polycarbonate Panel

The results show that the required pressure for testing the design and MSHA approval was not met. While reaching the peak pressure is not a problem within the shock tube, creating the prescribed waveform presents a difficult 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 4 PSI), the waveform duration was longer and showed promising results. However, damage to the shock tube did not allow for further investigation during this test series. Therefore, development, implementation, and the ability to replicate the same charge size every time of this system to a full scale experiment is currently being researched.

3.3 Additional Reduced Size Polycarbonate Wall Testing

3.3.1 Additional Reduced Size 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 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 91 inch x 91 inch opening. The smaller design included the full design height of six feet and used the whole 91 inch width. Also, one centered 66 inch x 38 inch polycarbonate panel was used along with two smaller 66 inch x 26.5 inch panels on either side. The vertical uprights 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 these uprights being for a 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. One inch roof bolts, as shown in Figure 3.20, were installed on top to lock the oak boards and steel frame together; regular half inch bolts were used to secure the bottom channel of the wall system frame to the floor of the shock tube. 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 3.21.

Figure 3.20. Roof Bolts Installed

Figure 3.21. Constructed Smaller Polycarbonate Wall System for Additional Testing

3.3.2 Additional Reduced Size Polycarbonate Wall Testing

The additional testing also used pressure sensors to measure the explosive 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 upright half way up each panel as shown in Figures 3.22 and 3.23. 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 45 or 30 feet from the wall. This round of testing consisted of five tests.

Figure 3.22. Sensor Placement for Additional Testing

Figure 3.23. Sensor Embedded in Polycarbonate Panel

3.3.3 Additional Reduced Size Polycarbonate Wall Testing Results

The reduced size 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 3.2.

Table 3.2. Additional Testing of Polycarbonate Wall System Results

Test Number	C4 Charge Weight (g)	C4 Charge Distance (ft)	Deflection (in)	Average Pressure (psi)	Average Impulse (psi-ms)	Laser Location
10191201	400	45	1.367989	13.49	65.11	Center of middle polycarbonate panel
10191202	500	45	1.522885	14.31	83.08	Center of middle polycarbonate panel
10191203	600	45	1.962377	15.43	101.21	Center of middle polycarbonate panel
10191204	650	45	2.278196	16.06	107.81	Center of middle polycarbonate panel
10191205	900	30	3.097167	25.56	150.07	Center of middle polycarbonate panel

As the results show, the wall was able to withstand up to 25.56 PSI without failing structurally. 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 as seen in Figure 3.24. This is not a cause of concern since the roof bolts were still in place to connect all of the size adjustment 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 and also as the number of bolts sheared off decreasing the rigidity of the system.

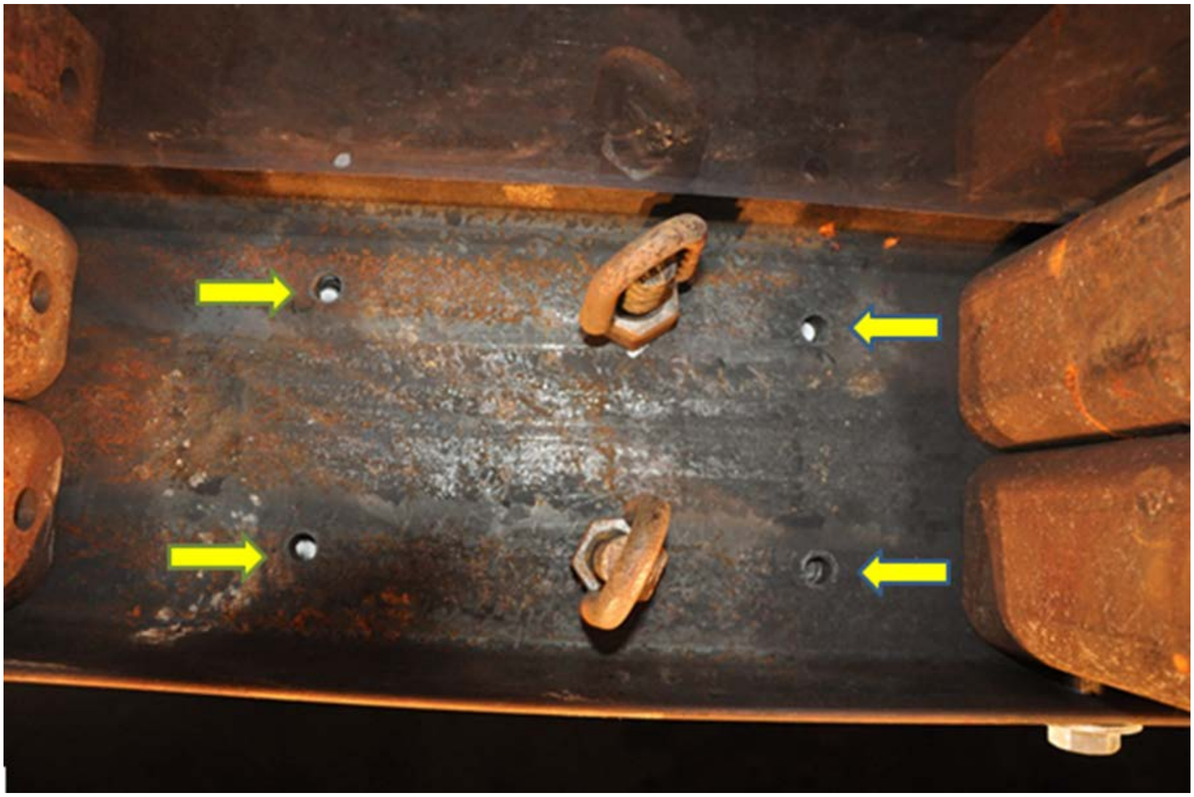


Figure 3.24. Sheared Bolts Connecting Channels

An approximately 20 and 12 inch crack developed following the final test in the center polycarbonate panel as seen in Figure 3.25. There was also a smaller three inch crack that was developed from previous testing as seen in Figure 3.26, 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 induced 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 Figure 3.25 shows. As a result, it is recommended that the bolts be hand tightened against the polycarbonate followed by a one second pulse from a 300 ft-lbs impact wrench to avoid over tightening.

Figure 3.25. Crack in Polycarbonate Following Final Test

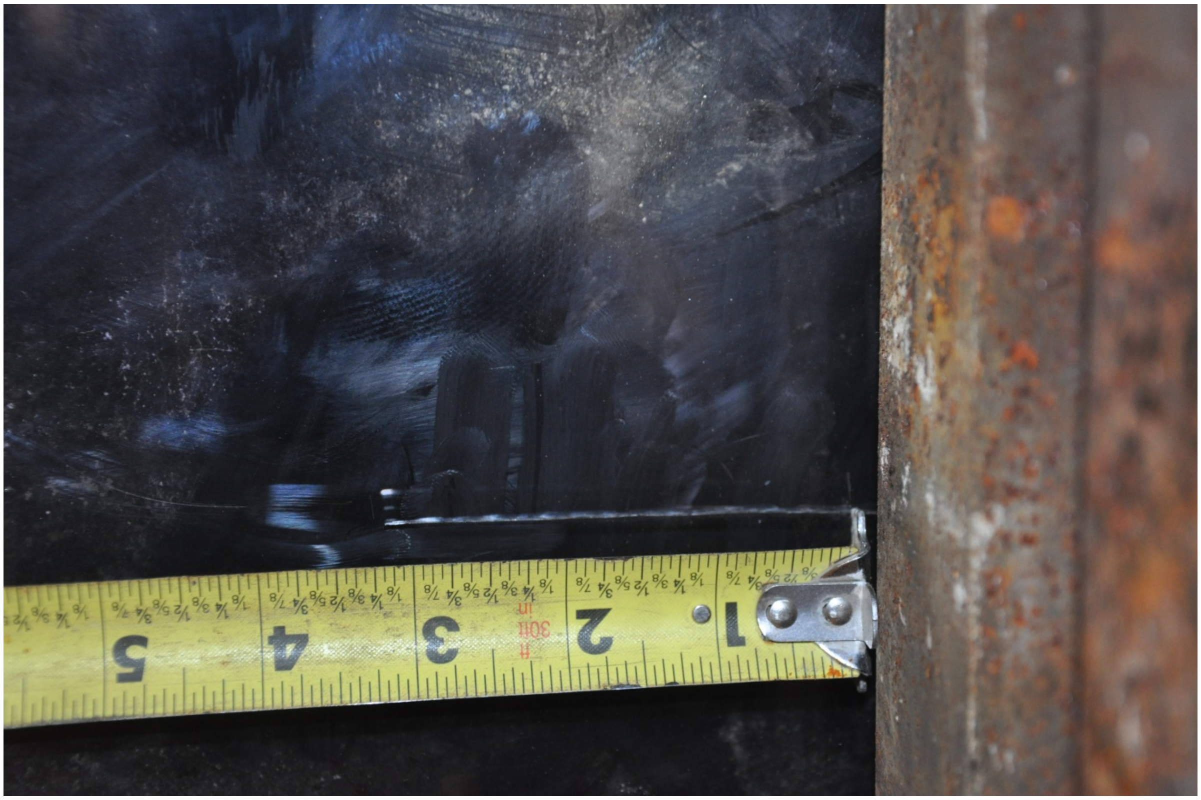


Figure 3.26. Crack from Previous Testing

The results from the additional testing of the reduced size wall system allow the research to achieve the goal of developing a design that can withstand 15 PSI blast pressure. In all, the wall was tested nine times and demonstrated that it is a strong design capable of withstanding multiple blasts of over 15 PSI. Even though the impulse 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.

3.4 Door System Testing

3.4.1 Door System Construction

The polycarbonate safe haven wall door system testing was performed after its installation in the underground coal mine, which will be discussed in Chapter 4, due to its availability. The door system was installed in the smaller framing system as discussed in section 3.3. Due to the door system being designed for a 32 inch opening for the underground mine installation, one of the center uprights had to be widened two inches to accommodate it. Once the upright was positioned, the polycarbonate door panel was fit to the newly positioned upright's bolt holes. With the holes in the polycarbonate matching those of the steel uprights, the 0.75 inch thick circular polycarbonate door and hinges were attached to the rest of the polycarbonate panel and steel. The hinges for the door bolted through the polycarbonate and steel frame just as the bolts holding the polycarbonate panels to the uprights. The latch mechanism was also similarly installed at this point through one bolt hole as seen in Figures 3.27 and 3.28. Finally, since one upright was widened, the old polycarbonate panel connected to the widened upright had to be reduced and new holes drilled to fit new system. The installed door system for testing can be seen in Figure 3.29 – 3.32.

Figure 3.27. Inside View of Latch Mechanism

Figure 3.28. Outside View of Latch Mechanism

Figure 3.29. Installed Door System for Testing (Inside)

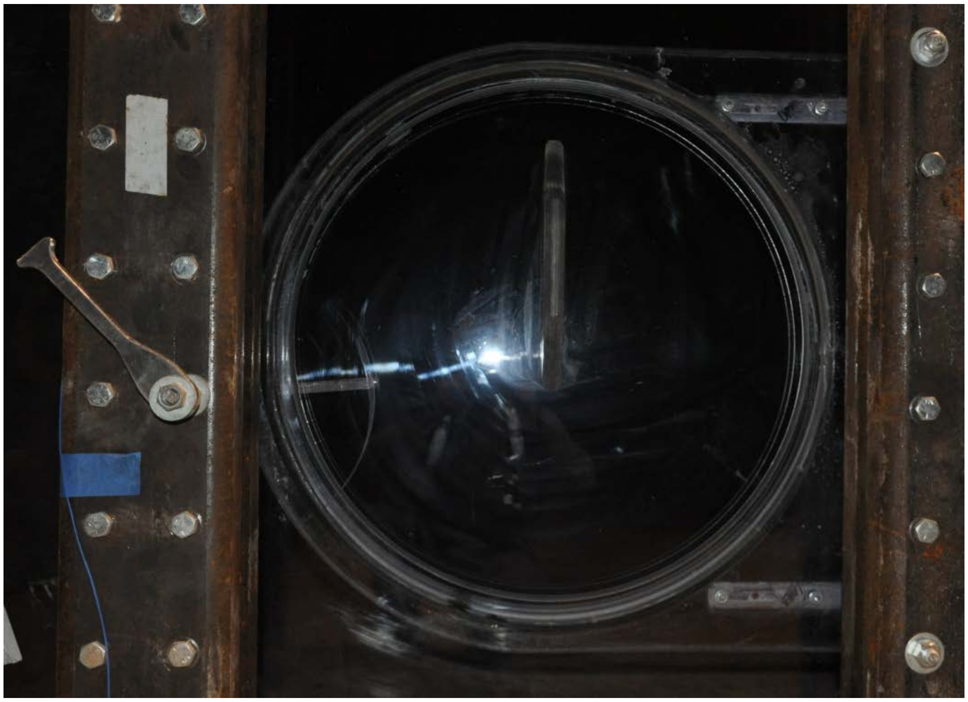


Figure 3.30. Installed Door (Inside)

Figure 3.31. Installed Door System for Testing (Outside)

Figure 3.32. Installed Door (Outside)

3.4.2 Door System Testing

The polycarbonate safe haven door system testing again used pressure sensors to measure the explosive pressure being experienced by the door and wall. The testing setup for the door system testing used two pressure sensors in the polycarbonate just outside each center vertical support just as the additional wall testing. The first sensor was placed half way up the left panel and the second was placed 24 inches up from the bottom of the right panel as seen in Figure 3.33. 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 45 feet from the door system. This round of testing consisted of three tests.

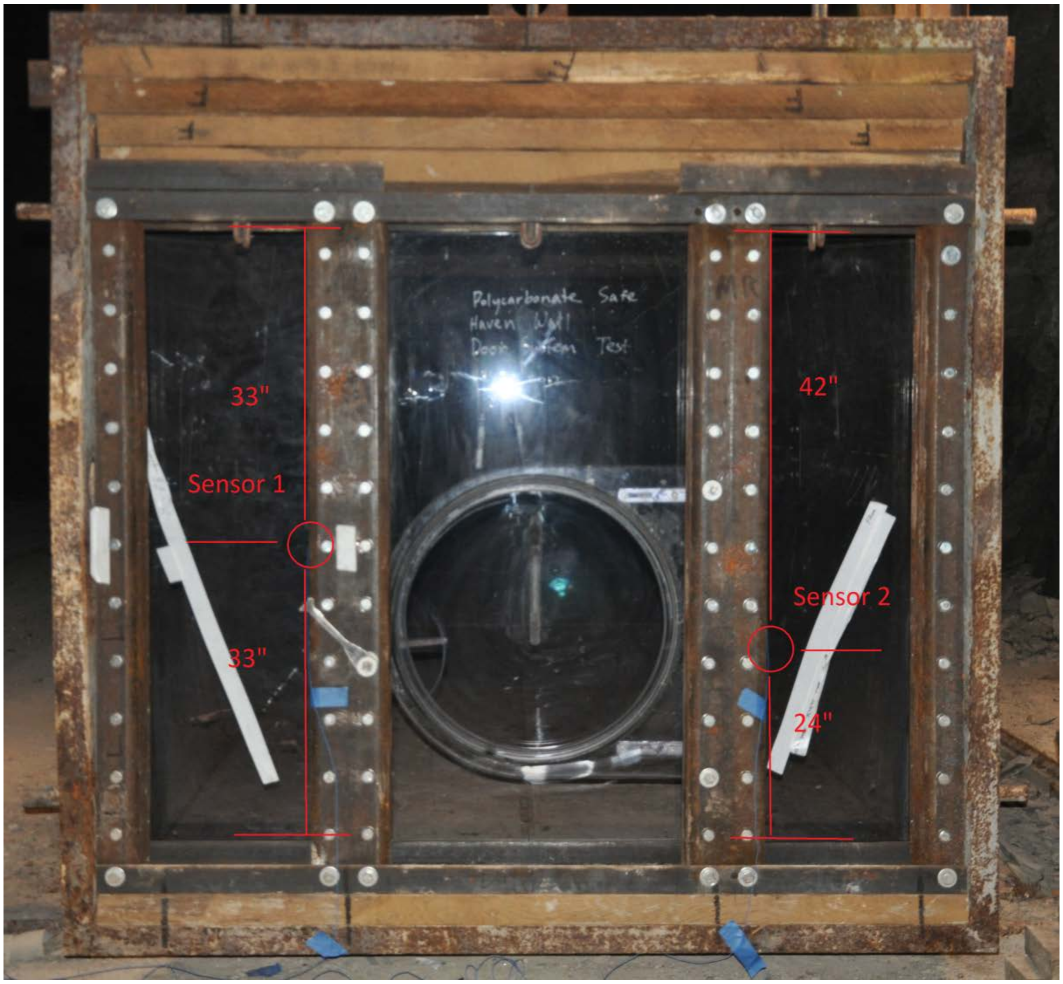


Figure 3.33. Sensor Arrangement for Door Testing

3.4.3 Door System Results

The door system performed exceptionally well during the blast testing. The design held up to all three tests and no damage occurred to any portion of the system. The latch mechanism and hinges were also still tight, operational, and structurally sound after each test. The pressures and impulses from the blast testing were recorded and can be seen in Table 3.3.

Table 3.3. Door System Results

Test Number	C4 Charge Weight (g)	C4 Charge Distance (ft)	Average Pressure (psi)	Average Impulse (psi-ms)
12201201	650	45	15.26	101.13
12201203	650	45	15.34	108.11
12201204	750	45	16.58	127.61

As the table shows, the door system was also subjected to 15 PSI blast pressures multiple times and showed no damage. Again, the impulse is below the MSHA specification; however, the results from the door system prove that the door system design is strong and provides a quality option for travel through the polycarbonate safe haven wall system.

CHAPTER 4. INSTALLATION IN UNDERGROUND COAL MINE

4.1 Introduction

The final task for the project was to install the full polycarbonate safe haven wall design in an underground coal mine. To achieve this goal, the author along with other UKERT members traveled to a chosen mine near Hazard, KY to take the measurements required to determine material specifications. The materials were then procured and prepared for the underground construction process. The steel framing was measured and cut using a plasma table for convenience. Due to the approximate 20 foot width of the chosen coal mine crosscut, the wall system was cut into two sections, 110 and 120 inches respectively, to aid in building the design in the confined conditions of an underground coal mine. The height of the wall was 82 inches, just under the height of the roof in the mine to allow for any inconsistencies in the roof height and space to stand up the wall. The bolt system was the same as the previously tested design with addition of two bolts vertically since the wall was almost one foot taller. Finally, the door system described earlier was also developed and assembled in the frame before being transported to the mine as one piece.

4.2 Underground Installation

The installation in an underground coal mine began by positioning the shorter preassembled door portion of the frame. This was done using clevises clipped into roof bolt plates already in the roof and chain hoists as seen in Figure 4.1 to lift the section up to a vertical position. Once the section was standing up, it was slid into position with the aid of a mining scoop machine. With the shorter channel section and door in position, 18 inch Hilti anchor bolts were inserted into the roof and floor through previous drilled holes in the top and bottom channel to secure the frame.

Figure 4.1. Chain Hoist Clipped in a Clevis Hooked into a Roof Bolt

The installation of the door and shorter channel frame took one hour and 15 minutes. Using the preassembled door allowed the construction time of the wall to be reduced by an estimated three hours. The installed door section can be seen in Figure 4.2.

Figure 4.2. Installed Preassembled Door and Shorter Channel Section

With the shorter channel frame sections installed, the next upright being placed in that section was able to be slid in the channel and bolted up as shown in Figure 4.3. Once the second upright was installed, the opening for the first polycarbonate panel was measured allowing the panel to be cut to size. After the panel was to size, it was placed against the steel frame uprights and marked for where the bolts holes needed to be drilled. While this was all taking place, the longer section of channel framing was being measured to fit the remaining opening. Bolt holes were also measured for the end upright against the rib and cut using an oxygen-acetylene torch. These processes took one hour to complete.

Figure 4.3. Second Vertical Support Installed

The next step in the installation process was to assemble the second longer section of channel frame and uprights. It was decided that the best way to install this section was to bolt the upright going against the opposite rib of the door to the top and bottom channel frame while on the ground. Then, the same method of clevises and chain hoists was used to lift the frame into place. Once the one upright and remaining channel frame was in place, the last three uprights were again slid into the channel and bolted to the channel. The channel frame had to be left at an angle in order to allow enough space between the already installed shorter channel section to slide in the uprights. With all the uprights bolted to the channel frame, the whole section was aligned with the first section using a sledge hammer and pry bar. It was then bolted to the floor and roof using the Hilti bolts as seen in Figure 4.4. Meanwhile, during this process the one polycarbonate panel that was measured was drilled and installed. These processes took one hour and 25 minutes and the results can be seen in Figure 4.5.

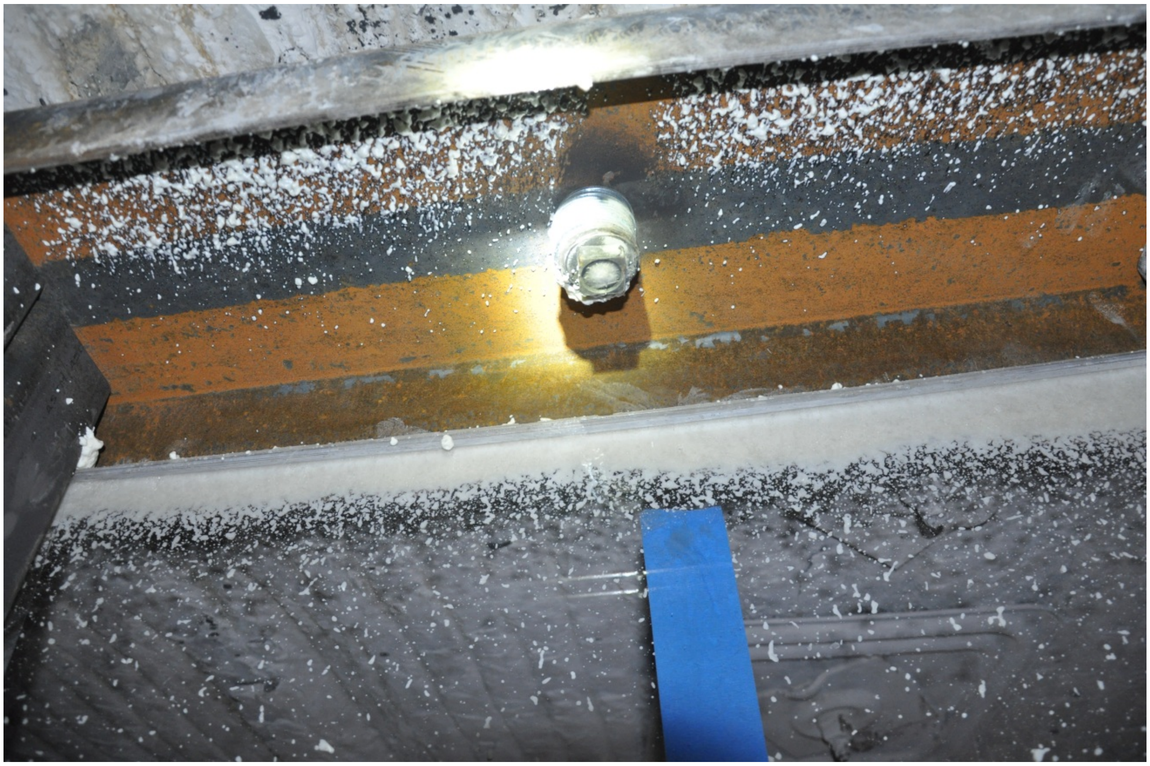


Figure 4.4. Installed Hilti Bolt

Figure 4.5. Completed Framing Installation

Following the installation of the steel frame, the remaining processes included measuring the polycarbonate panels to fit the openings between each vertical upright, marking bolt hole locations, drilling the holes, and installing the panels. This process was the most time consuming of the whole wall installation due to the limitations of tools and power. The polycarbonate panels were cut to size using a circular saw and drilled using forester bits while sitting on saw horses as seen in Figure 4.6. The installation of the remaining four panels took three hours and 15 minutes and the completed installation can be seen in Figure 4.7. All the bolts were tightened using a wrench and impact wrench at the before recommended tightening method to avoid cracking the polycarbonate.

Figure 4.6. Cutting and Drilling Polycarbonate Panels

Figure 4.7. All Polycarbonate Panels Installed

With the polycarbonate wall system installed, the final step was to seal the gaps with expanding Mine Foam. The areas seen in Figures 4.8 and 4.9 are where plywood was cut and placed to help fill gaps left between the wall and ribs due to irregular shapes of the ribs. The spaces left between the wall and the roof along with gaps between the steel frame and polycarbonate panels were all sealed with foam as seen in Figures 4.10 and 4.11. Sealing of the wall with the foam was done to verify the wall as a safe haven since it is required to maintain a stable, air-tight atmosphere. This process took 25 minutes.

Figure 4.8. Mine Foam Covered Plywood Used to Seal the Wall

Figure 4.9. Plywood and Mine Foam Used to Help Seal the Wall

Figure 4.10. Mine Foam Sealing the Space between the Frame and Floor

Figure 4.11. Mine Foam Sealing the Space between the Frame and Polycarbonate and Roof

The polycarbonate safe haven wall installation and sealing was performed by eight people and took a total time of 7 hours and 20 minutes. A time limit goal of one shift was set prior to installation by the project team and that goal was met since mining shifts are normally no less than eight hours. Therefore, the safe haven wall design installation is a comparable and justifiable alternative in its current design, meeting one goal of the research. The completed installation measured 228 inches wide and 82 inches tall. The door section provided a 32 inch opening, while the middle four sections were 30 inches, and the far left panel was 20 inches as seen in Figure 4.12. All of the polycarbonate panels were ¾ inch thick including the door panel. The final sealed installation is shown below in Figure 4.12 and 4.13.

Figure 4.12. Final Sealed Installation Outside

Figure 4.13. Final Sealed Installation Inside

CHAPTER 5. CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS

5.1 Conclusion

The research project was able to produce a successful safe haven wall design through both modeling and testing and then proved feasible with the construction within an active coal mine. The design met all project goals of being lightweight for easy installation, transparent to allow trapped miners to be easily identified and rescued, able to be installed in one shift, and provide cost advantages over currently used refuge alternatives. The polycarbonate safe haven wall system was also able to withstand 15 PSI blast pressure multiple times although the impulse was not reached. However, models showed it was able to withstand the MSHA required blast pressure and impulse. The successful design was made out of HSS 8x4x0.5 inch vertical supports and held in place by C10x10 channel with one inch polycarbonate panels bolted to the uprights. The dimensions of the design were able to reach an installed width of 228 inches and a height of 82 inches. A door system for the polycarbonate safe haven wall was also successfully developed to allow easy passage through the wall system and installed as part of the wall system in an underground coal mine. The door system was also able to withstand 15 PSI blast pressures multiple times. With the research complete and all goals achieved, there is still room for improvement in the design along with the installation processes to help develop new safe haven alternatives for use in underground coal mines.

5.2 Overall Cost Advantage

One of the main objectives of this research was to develop an alternative to refuge options currently available to underground coal mines. The typical method mines use is refuge chambers which can cost well upwards of $80,000 depending on personnel capacity. With the use of safe haven walls, walls can be constructed on both ends of a crosscut with lifesaving/sustaining supplies stored between the walls. Another option which would only require one wall consists of a room created by the continuous miner into a solid coal block. Three walls of the room would be coal while the opening could be closed with a wall.

The designed polycarbonate safe haven wall consists of four main components which greatly influence the overall cost: polycarbonate, steel, door fabrication, and bolts. While not every polycarbonate wall will be identical due to changing cutting heights and widths, a summary of the costs for the seven foot wall installed in the mine are given in Table 5.1. The steel support line includes the C-Channel and the vertical hollow structural sections. The bolts line item includes the bolt, washers, and nut.

Table 5.1. Material Cost for a Seven Foot Polycarbonate Safe Haven Wall

Item	Unit Price	Quantity	Price
Polycarbonate Panel	$1,161.37	6	$6,968.22
Steel Support	$3,931.00	1	$3,931.00
Door Fabrication & Drilling	$2,853.00	1	$2,853.00
Grade 50 0.75 inch Bolts	$5.83	180	$1,049.40
	Material Cost		**$14,801.62**

The constructed wall was approximately 7 feet tall and 20 feet wide which would be sufficient cover a large portion of the underground coal mines in Kentucky. In addition, mines can plan in advance where to station these walls so that cutting height and width can be slightly reduced to decrease the overall costs of the wall. The price shown in Table 5.1 does not include everything that would be required to install the wall. Several point-anchor bolts, as described in the previous section, will be required. Material to seal the air gaps will also be required.

The total material cost of $14,800 was for this prototype design. With the addition of materials not listed in the table, a total material cost of approximately $16,000 is realistic and reasonable. For a total installed cost, mining personnel and equipment usage must be accounted for. After construction and installation of the prototype, it is believed that several time-consuming steps could be done prior to taking the materials underground (e.g. polycarbonate drilling and some steel structure assembly). However, the prices shown in Table 5.2 include the costs of three miners for an eight hour shift as well as a piece of equipment (a mine scoop) used for two hours.

Table 5.2. Total Installed Cost of Polycarbonate Wall

Item	Unit	Quantity	Hours	Price
Material	$16,000	1	N/A	$16,000
Mining Personnel	$75	3	8	$1,800
Equipment Usage (Scoop)	$250	1	2	$500
		Installed Cost		**$18,300**

A $18,300 price tag for an installed safe haven wall will be a very attractive for mine operators in Kentucky and throughout the region. Even when two walls are required, the total installed cost will be less than half of currently implemented refuge chambers. Adding an estimated cost of $200 per person for supplies such as food, water, and other consumables required by MSHA to afford trapped miners a life-sustaining environment to complete the safe haven, the final product would be competitive from a cost standpoint. Another cost saving measure will be the volume of materials ordered. As with most goods, volume pricing will further decrease the overall costs to these mines.

When compared to concrete block walls, the material costs of the polycarbonate panel are higher than that of block and mortar. However, there are several advantages polycarbonate has over the block walls. First, the construction time of double, or triple wythe concrete blocks can take anywhere from 1-3 shifts depending on mining location. Second, the material handling of the heavy concrete blocks can lead to injuries to mining personnel. While the steel of the polycarbonate wall is also heavy, equipment can aid in movement and placement versus each individual concrete block requiring a miner to carry and place them. Third, all materials required for the entire polycarbonate wall were transported from the surface to the location using a single scoop with trailer and then unloaded by hand. Finally, the polycarbonate wall is clear while the concrete blocks are not. In the event of an explosion, mine rescue teams can simply look through the wall to see if any miners are taking refuge inside. For concrete block walls, a large, heavy door must be opened. This task is time consuming and may not allow teams to reach miners in distress.

One final cost saving measure is that the polycarbonate panels are detachable and movable. As the panels consist of approximately half of the material cost, this can be a great advantage. With standardized sizes within a mine, the polycarbonate panels can be unbolted from the steel frame and moved wherever they are needed. For example, in mines where sections are sealed off and never to be revisited, the panels can be unbolted and re-installed on new steel frames elsewhere in the mine. While this concept may not be beneficial in an active mining section, removing them from soon to be sealed off areas is a great way for the mines to save money. This option is not possible with concrete block walls. Therefore, in larger mines where multiple walls are constructed, the total cost of the polycarbonate safe haven wall may be lower for the overall life of the mine.

5.3 Future Installation Revision Suggestions

The installation of the polycarbonate safe haven wall system was a success. However, there are a few issues that need revision following the first installation in an underground coal mine. First, a three inch by six inch steel plate needs to be installed on the outside of each channel to help connect the two sections of steel channel framing. As Figures 5.1 and 5.2 show, the two channel sections of the frame did not align very well. This became apparent when trying to align the two sections during installation to create a square wall. Consequently, this created a difficult situation when trying to install the vertical supports.


Figure 5.1. Intersection of the Top Two Channel Sections


Figure 5.2. Intersection of the Bottom Two Channel Sections

A second recommended revision would be to develop a better method of sealing between the wall and the coal pillars on each side. Expanding Mine Foam was used for the prototype installation but would not provide enough resistance over that span in case of an actual explosion. In future installations, bags which can be filled with a cementious grout should be placed between the wall sides and coal pillar and then filled. The expanding bags will fill the void and provide sufficient resistance in the event of an explosion. These bags have been used in coal mines in the past for 20 PSI mine seals and have been proven to be an effective solution to this type of scenario.

A third revision would be to the door system. For the first iteration, the door performed very well, however, it did not seal very well because of the flex in the polycarbonate. A steel frame surrounding the circular polycarbonate window would help add rigidity to the door and allow it seal better. There are also alternative latching mechanisms that could be used to ensure a higher quality seal.

There is a possibility that the wall could be constructed outside the mine in two pieces. In this situation, the two panels would be taken into the mine completely fitted with polycarbonate and uprights. The only tasks remaining underground would be standing up the sections and attaching them to the roof and floor and aligning them to each other with a steel plate for square installation. The wall could then be sealed with grout bags and mine foam. This would allow for further reduction in installation times.

Finally, proper drilling equipment is needed to properly install the Hilti anchor bolts. During installation, the drill being used had problems drilling through the floor and roof causing the bolts to require washers to make up the distance to allow the bolts to anchor properly as shown in Figure 5.3. For this being the first installation, the process went very well but these revisions would aid in the design and installation process for future iterations.

Figure 5.3. Polycarbonate Washers used on Hilti Bolts

5.4 Recommendations for Future Work

There are several areas in which this work can be continued. One of the most obvious research avenues includes improving the door system for the safe haven wall. The door system was merely a first iteration for the performed research and has a lot of room for potential growth. Some of the ideas for further enhancement of the door system have been previously mentioned in this chapter and include: a stronger frame for the polycarbonate door and alternative latching devices. Research in this area could provide the wall system with a standard design that could be mass produced to help decrease the overall cost of the wall. It would beneficial to look into current doors on refuge chambers for improving design considerations. The latching mechanism can also be researched to optimize the sealing of the door to help maintain a stable atmosphere inside the safe haven.

The polycarbonate wall system also needs additional experimental testing using explosives. The wall was able to withstand the MSHA prescribed 15 PSI blast pressure; however, the desired impulse could not be achieved. Further research on how to replicate the desired wave form must be performed to ensure the wall can withstand the proper blast requirement. The production of the desired wave form may have to come from the use of different gas mixtures or timing of explosive charges to increase the duration of blast. This sort of testing may need to be performed in a non-metal mine atmosphere to also verify the utility of the anchorage and sealing of the wall system.

Further research needs to be performed on the proper way to seal the polycarbonate wall system. Since the opening size and conditions will vary for each wall placement, an improved method for filling the void space between the wall and the surrounding coal needs to be designed. The use of bags filled with cementious grout has been successfully used to fill the void space when building 20 PSI mine seals. The expandable bag can form to each surface providing an adequate seal and resistance in the event of an explosion.

Finally, the design of the support structure needs to be examined. There are other non-steel support options that can possibly provide similar strength and reduce the support weight to help reduce the labor requirement to construct the wall. Telescoping supports would also help the versatility of the wall and possibly reduce the size of the supports needed to withstand a blast. These types of supports could be mass produced to work in any type of mine site and in turn, reduce the overall cost of the safe haven wall system. The need for new refuge alternatives should provide the needed support and funding for continuing this type of research.

APPENDIX A

HazL output for 0.75 Inch MSHA Curve.

```
HazL v1.2 Analysis Details

HazL - Tue,  Jan 15, 2013, 19:24

================

INPUT PARAMETERS

================

Analysis Mode : Threat Analysis

System Of Measure: English

Hazard Level Based on: Flight

Threat Input:

------------

Load read from file      = C:\Users\Braden\Documents\HAZL\Useful Output\MSHA 15

PSI Curve.csv

Window Input:

-------------

Stiffness                = Moore Resistance Function

Glazing Type             = Polycarbonate

Prob of fail (#/1000)    = 500.00

Height                   = 30.00 in

Width                    = 30.00 in

Actual Thickness         = 0.750 in

Ht. of sill above floor  = 2.00 in
```

```
===============

RESULTS SUMMARY

===============

Window Parameters

-------------------

Xu          =  2.964 in        Maximum Static Deflection

Ru          =  39.96 psi       Maximum Effective Static Capacity

Bite        =  0.887 in        Required Bite

Stress      =  9500.00 psi     Peak Glass Stress


Window Response

---------------------

Glass does not crack and is retained in frame.

==============================

  Hazard level = No Break

==============================

Peak glass stress     = 4921.160769 psi

Maximum acceleration       = 268.96 g's at 91.97 ms

Maximum velocity    = 221.70 in/s at 95.21 ms

Maximum displacement      = 2.14 in at 97.76 ms

Minimum acceleration       = -2059.39 g's at 0.17 ms

Minimum velocity    = -203.14 in/s at 100.49 ms

Minimum displacement      = -0.53 in at 206.43 ms
```

Static Edge Shears - Glazing Only:

VX = 593.40*SIN(0.10*X) + 39.96*W lbs/in

VY = 593.40*SIN(0.10*Y) + 39.96*W lbs/in

R = -2337.65 lbs

- X in the above equation varies from zero up to the long dimension of the window in inch.

- Y in the above equation varies from zero up to the short dimension of the window in inch.

- W in the above equations is the width of the window frame that is exposed to blastin inch.

- R in the above equations is the uplift corner force in pounds.

Dynamic Edge Shears - Glazing Only:

VX = 6311.18 lbs or 210.37 lbs/in

VY = 6311.18 lbs or 210.37 lbs/in

APPENDIX B

HazL output for 1 Inch MSHA Curve.

```
HazL v1.2 Analysis Details
HazL - Tue,  Jan 15, 2013, 19:29
================
INPUT PARAMETERS
================
Analysis Mode : Threat Analysis
System Of Measure: English
Hazard Level Based on: Flight
Threat Input:
------------
Load read from file      = C:\Users\Braden\Documents\HAZL\Useful Output\MSHA 15
PSI Curve.csv
Window Input:
-------------
Stiffness                = Moore Resistance Function
Glazing Type             = Polycarbonate
Prob of fail (#/1000)    = 500.00
Height                   = 30.00 in
Width                    = 30.00 in
Actual Thickness         = 1.000 in
Ht. of sill above floor  = 2.00 in
```

```
===============

RESULTS SUMMARY

===============

Window Parameters

-------------------

Xu                  =  2.824 in                Maximum Static Deflection

Ru                  =  64.84 psi               Maximum Effective Static Capacity

Bite                =  0.852 in                Required Bite

Stress              =  9500.00 psi             Peak Glass Stress

Window Response

---------------------

Glass does not crack and is retained in frame.


 ==============================

   Hazard level = No Break

==============================

 Peak glass stress        = 3521.587137 psi

 Maximum acceleration          = 193.57 g's at 89.74 ms

Maximum velocity     = 170.85 in/s at 93.12 ms

Maximum displacement          = 1.45 in at 95.88 ms

Minimum acceleration          = -2313.91 g's at 0.15 ms

Minimum velocity     = -154.90 in/s at 110.48 ms

Minimum displacement          = -0.33 in at 3.84 ms
```

Static Edge Shears - Glazing Only:

VX = 962.82*SIN(0.10*X) + 64.84*W lbs/in

VY = 962.82*SIN(0.10*Y) + 64.84*W lbs/in

R = -3792.94 lbs

- X in the above equation varies from zero up to the long dimension of the window in inch.

- Y in the above equation varies from zero up to the short dimension of the window in inch.

- W in the above equations is the width of the window frame that is exposed to blastin inch.

- R in the above equations is the uplift corner force in pounds.

Dynamic Edge Shears - Glazing Only:

VX = 9451.48 lbs or 315.05 lbs/in

VY = 9451.48 lbs or 315.05 lbs/in

APPENDIX C

HazL output for 0.75 Inch Test Data Curve

```
HazL v1.2 Analysis Details
HazL - Tue,  Jan 15, 2013, 19:48
================
INPUT PARAMETERS
================
Analysis Mode : Threat Analysis
System Of Measure: English
Hazard Level Based on: Flight
Threat Input:
------------
Load read from file      = C:\Users\Braden\Documents\HAZL\Useful Output\Door Test Data curve.csv
Window Input:
-------------
Stiffness                = Moore Resistance Function
Glazing Type             = Polycarbonate
Prob of fail (#/1000)    = 500.00
Height                   = 30.00 in
Width                    = 30.00 in
Actual Thickness         = 0.750 in
Ht. of sill above floor  = 2.00 in
===============
```

```
RESULTS SUMMARY

===============

Window Parameters

-------------------

Xu          =  2.964 in         Maximum Static Deflection

Ru          =  39.96 psi        Maximum Effective Static Capacity

Bite        =  0.887 in         Required Bite

Stress      =  9500.00 psi      Peak Glass Stress

Window Response

---------------------

Glass does not crack and is retained in frame.

==============================

  Hazard level = No Break

==============================

Peak glass stress      = 4748.676789 psi

Maximum acceleration        = 774.67 g's at 0.17 ms

Maximum velocity     = 534.80 in/s at 3.24 ms

Maximum displacement        = 2.08 in at 5.96 ms

Minimum acceleration        = -935.96 g's at 6.13 ms

Minimum velocity     = -599.54 in/s at 8.52 ms

Minimum displacement        = -1.54 in at 66.25 ms

Static Edge Shears - Glazing Only:

-------------------
```

VX = 593.40*SIN(0.10*X) + 39.96*W lbs/in

VY = 593.40*SIN(0.10*Y) + 39.96*W lbs/in

R = -2337.65 lbs

- X in the above equation varies from zero up to the long dimension of the window in inch.

- Y in the above equation varies from zero up to the short dimension of the window in inch.

- W in the above equations is the width of the window frame that is exposed to blastin inch.

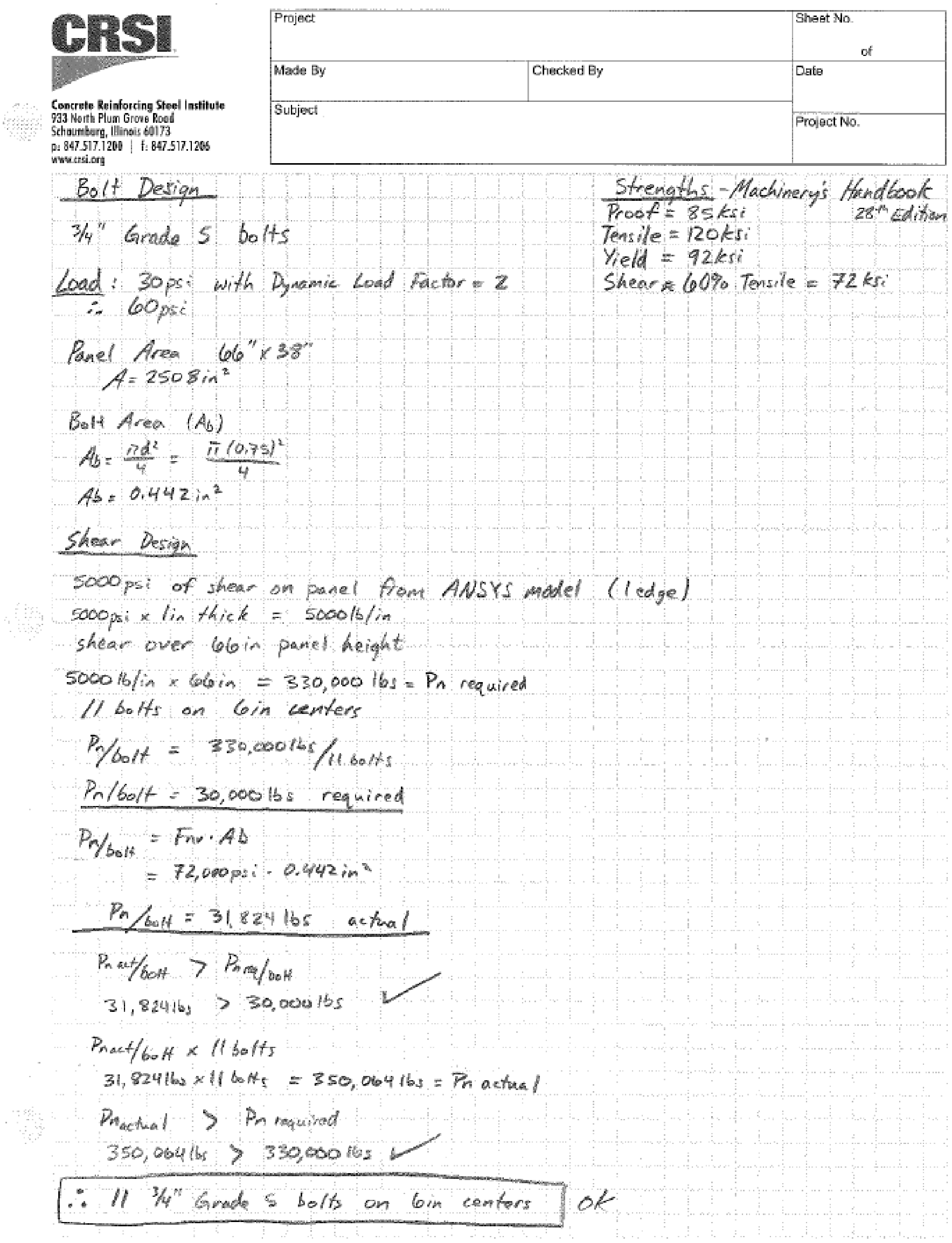
- R in the above equations is the uplift corner force in pounds.

Dynamic Edge Shears - Glazing Only:

VX = 3356.54 lbs or 111.88 lbs/in

VY = 3356.54 lbs or 111.88 lbs/in

APPENDIX D



CRSI
Concrete Reinforcing Steel Institute
933 North Plum Grove Road
Schaumburg, Illinois 60173
p: 847.517.1200 | f: 847.517.1206
www.crsi.org

Project			Sheet No. of
Made By		Checked By	Date
Subject			Project No.

Bolt Design

3/4" Grade 5 bolts

Load: 30psi with Dynamic Load Factor = 2
$\therefore$ 60psi

Panel Area 66" x 38"
$A = 2508 \text{ in}^2$

Bolt Area (A_b)
$A_b = \frac{\pi d^2}{4} = \frac{\pi (0.75)^2}{4}$
$A_b = 0.442 \text{ in}^2$

Strengths - Machinery's Handbook 28th Edition
Proof = 85ksi
Tensile = 120ksi
Yield = 92ksi
Shear $\approx$ 60% Tensile = 72ksi

Shear Design

5000psi of shear on panel from ANSYS model (1 edge)
5000psi x 1in thick = 5000lb/in
shear over 66in panel height

5000 lb/in x 66in = 330,000 lbs = Pn required
11 bolts on 6in centers

$P_n/\text{bolt} = 330{,}000 \text{ lbs} / 11 \text{ bolts}$

$P_n/\text{bolt} = 30{,}000 \text{ lbs}$ required

$P_n/\text{bolt} = F_{nv} \cdot A_b$
$= 72{,}000 \text{ psi} \cdot 0.442 \text{ in}^2$

$P_n/\text{bolt} = 31{,}824 \text{ lbs}$ actual

$P_{n\,act}/\text{bolt} > P_{n\,req}/\text{bolt}$
31,824lbs > 30,000 lbs ✓

$P_{n\,act}/\text{bolt} \times 11$ bolts
31,824lbs x 11 bolts = 350,064 lbs = Pn actual

$P_{n\,actual} > P_n$ required
350,064lbs > 330,000 lbs ✓

$\boxed{\therefore\ 11\ \text{3/4" Grade 5 bolts on 6in centers}}$ ok

CRSI
Concrete Reinforcing Steel Institute
933 North Plum Grove Road
Schaumburg, Illinois 60173
p: 847.517.1200 | f: 847.517.1206
www.crsi.org

Project		Sheet No. of
Made By	Checked By	Date
Subject		Project No.

Tension Capacity (failure)

$P_n = F_{nt} A_b$

$= 120{,}000 \text{ psi} \times 0.442 \text{ in}^2$

$P_n = 53040$ lbs/bolt

$P_n \times 11$ bolts

53040 lbs/bolt $\times 11$

$P_n = 583440$ lbs

Yield Strength (stretch)

$P_n = F_y A_b$

$= 92{,}000 \text{ psi} \times 0.442 \text{ in}^2$

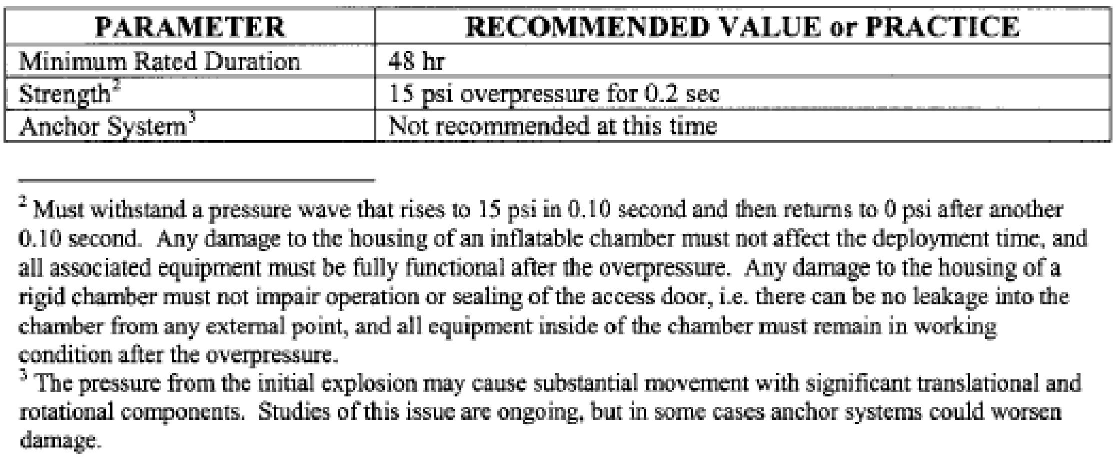
$P_n = 40{,}664$ lbs/bolt

$P_n \times 11$ bolts

$40{,}664$ lbs/bolt $\times 11$ bolts

$P_n = 447{,}304$ lbs

APPENDIX E



PARAMETER	RECOMMENDED VALUE or PRACTICE
Minimum Rated Duration	48 hr
Strength[2]	15 psi overpressure for 0.2 sec
Anchor System[3]	Not recommended at this time

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[2] Must withstand a pressure wave that rises to 15 psi in 0.10 second and then returns to 0 psi after another 0.10 second. Any damage to the housing of an inflatable chamber must not affect the deployment time, and all associated equipment must be fully functional after the overpressure. Any damage to the housing of a rigid chamber must not impair operation or sealing of the access door, i.e. there can be no leakage into the chamber from any external point, and all equipment inside of the chamber must remain in working condition after the overpressure.

[3] The pressure from the initial explosion may cause substantial movement with significant translational and rotational components. Studies of this issue are ongoing, but in some cases anchor systems could worsen damage.

PARAMETER	RECOMMENDED VALUE or PRACTICE
Fire Resistance [4]	300° F for 3 sec
Deployment Time [5]	Minimize this time when establishing the location of the refuge alternative and consider as part of the travel time
Min Concentration O_2	18.5%
Max Concentration O_2	23%
Max Concentration CO [6]	25 ppm
Gases to be Monitored Inside Chamber	O_2, CO, CO_2
External Gases to be Monitored	O_2, CO
Max Concentration CO_2 [7]	1.0%, not to exceed 2.5% for any 24-hr period
Apparent Temperature [8]	95° F
Entry and Exit	Provide a means of egress without contaminating the internal environment and/or a means to maintain a safe environment during and after ingress/egress
Potable Water per Person	2-2.25 qt per 24 hr
Durability [9]	Structurally reinforced and of sufficient physical integrity to withstand routine handling
Purge Air Volume [10]	No specific recommendation (see Entry and Exit parameter)
Food,[11] per Person	2000 cal per 24 hr
Human Waste Disposal System	Required
First Aid Kit	Required
Occupant-Activated Annunciation	Battery-powered strobe light or radio homing signal [12]
Communication with Surface[13]	Survivable post-disaster system
Minimum Distance to Working Face	1000 ft

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[4] This parameter is based on NFPA-2113, but additional investigation is warranted; a fire resistance specification should be selected to protect exposed surfaces from the initial, not a subsequent explosion.

[5] This is the elapsed time beginning with the arrival of miners at the location of the chamber and ending when the environmental systems within the chamber have begun to function. Additional work is needed to establish reasonable boundaries for this time frame. In the interim, deployment time should be considered as part of the travel time needed to reach a chamber.

[6] The concern here is CO contamination during ingress and egress (see purge air volume).

[7] Scrubber materials must not become airborne or otherwise cause respiratory distress or other acute reactions.

[8] Apparent temperature is a measure of heat stress, but other indices or standards could be used, such as the wet bulb temperature. Regardless of the index selected, the numerical value must be assigned to prevent heat stroke. Thus, if wet bulb temperature were selected, then a corresponding numerical value of 84 deg F would be appropriate, based on available medical evidence.

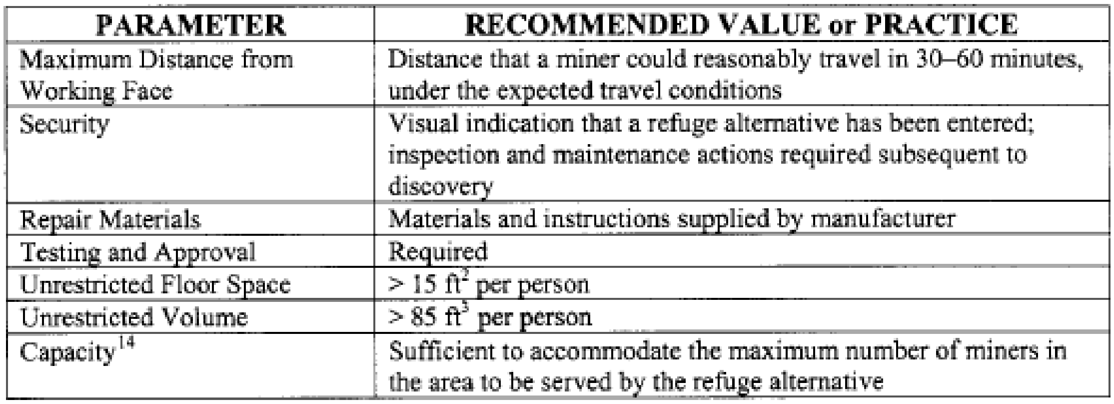
[9] The expectation is that the structure can withstand the expected number of moves without visible evidence of structural damage and without damage to the internal contents.

[10] It is unclear whether all commercial chambers can purge contaminated air from the chamber; this will require further investigation.

[11] Food stores should be selected to minimize waste and flatulence and to meet basic nutritional needs.

[12] This would allow rescue teams to concentrate their efforts on refuge alternatives that are occupied. The use of the battery in this application is controversial and additional study is warranted.

[13] Systems are under development and should be applied as soon as they become available. These systems should be independent of the mine's communications system, to the extent practicable.



PARAMETER	RECOMMENDED VALUE or PRACTICE
Maximum Distance from Working Face	Distance that a miner could reasonably travel in 30–60 minutes, under the expected travel conditions
Security	Visual indication that a refuge alternative has been entered; inspection and maintenance actions required subsequent to discovery
Repair Materials	Materials and instructions supplied by manufacturer
Testing and Approval	Required
Unrestricted Floor Space	> 15 ft^2 per person
Unrestricted Volume	> 85 ft^3 per person
Capacity[14]	Sufficient to accommodate the maximum number of miners in the area to be served by the refuge alternative

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VITA

Rex Allen Meyr Jr. was born in Cape Girardeau, Missouri to Rex and Patricia Meyr. He attended the University of Missouri in Columbia, Missouri, and was awarded a Bachelor of Science Degree in Civil Engineering with Cum Laude honors. Upon graduation, he moved to Lexington, Kentucky to attend the University of Kentucky to study Mining Engineering. He was awarded a fellowship and worked as both a research and teaching assistant to Dr. Kyle Perry. He expects to graduate in May 2013 with a Master of Science in Mining Engineering. He has been a member of both SME and ISEE since 2011.