Analysis and redesign of mine bearing plates

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ABSTRACT

This paper discusses optimization analysis performed on a recently patented rock bolt mine bearing plate design. Mine bearing plates are used to help secure the ceilings of underground mines.

The improved mine bearing plate was to conform to the mine ceiling when in use. Due to anticipated plastic behavior, the analysis required material properties in that region of the stress strain curve. Finite element analysis was performed on the plate in order to meet strength and flexibility requirements. Using the finite element program Ansys, various configurations of material type and thickness were analyzed in a loading scenario which simulated the American Society for Testing and Materials (ASTM) designation F432.

Plates which met the ASTM criteria were reviewed and the optimized design was selected.

INDEX TERMS

AISI 1018 CW plastic analysis, Mine bearing plate, Rock bolt application

I. INTRODUCTION

Roof bolt bearing plates have been used in underground mining operations for many years. The bearing plates are a component of the system used to secure underground mine roofs for the safe passage of mine workers.

An inventor recently designed and patented a new roof bolt mine bearing plate that addresses several shortcomings of the design in current use. Unfortunately, the new design failed critical ASTM testing, leaving the non-technical inventor unsure of what modifications were needed to pass certification testing. The University of Pittsburgh at Johnstown Department of Mechanical Engineering Technology was contacted to analyze and optimize the design.

II. BACKGROUND

Underground mining operations use roof bolt bearing plates to support the roofs in underground mines. Support integrity for the mine roof provides a safe work environment and maintains the important safety requirements for working in an underground mine. Failure to control the stability of the roof of the mine leads to the majority of serious or fatal accidents occurring in underground mines in the United States today. Accordingly, mine roof control systems must provide safety integrity for personnel working in the mines. The Mine Safety and Health Administration (MSHA) of the United States government enforces mine safety standards, including roof support standards, and inspects mine roof control plans and practices in the mining industry [1].

Enhanced safety and roof support systems have reduced serious accidents involving major roof cave-ins substantially since the 1970s, but there is still need for improvement. According to the MSHA web site, the Sago Mine in West Virginia had 28 roof falls in the period from February 2004 to December 5, 2005. Fortunately, only one resulted in an injury [2]. Compliance with MSHA standards requires underground mines to have a roof control plan in place, and such a plan includes “primary roof support.” Primary roof support includes abatement provisions designed to prevent a roof cave-in by sealing the lowest layers of a mine roof to the upper strata of rock.

Methods for attaching lower level rock strata to upper layers use a roof bolt and epoxy resin to seal the bolt to layers of rock strata. Roof bolts vary in length

and size but are typically 1.27 mm (0.5 inches) or more in diameter and 762 mm (30 inches) to 3.66 meters (12 feet) long or longer in overall length. After a borehole is placed in the roof, epoxy resin in a pliable plastic tube is inserted in the hole. Next, a roof bolt is placed in the hole. The placing of the roof bolt tears the packaging of the epoxy resin and mixes the resin to the bolt itself and the surrounding rock layers. Once the epoxy resin hardens, it bonds the steel bolt to the rock layers. After allowing the resin to fully harden, the mine bearing plate is attached to the threaded bolt end protruding from the ceiling using a nut. As the nut is tightened, the mine bearing plate spreads the tensile loads in the system away from the collar of the borehole to the more competent surrounding rock [3].

In most underground mining situations, a roof bolt is placed approximately every four feet in the mine. Accordingly, the roof support is a major undertaking and a major source of expense for the mine operator [1].

III. PROBLEM STATEMENT

A. *Designs*

The bearing plate designs currently in use have several shortcomings. Conventional roof support designs are square, often embossed in such a way that the corners protrude down into the mine cavity (see Figure l and Figure 2) [4].

Figure 1. Typical application

Figure 2. Typical existing design

The improved mine bearing plate, as initially presented, was a one-piece, pressed structure of ASTM A-36 steel. The improved design is round thus eliminating the dangerous corners which protrude downward in the conventional design. During application of the improved mine bearing plate, the center section is drawn inward by the nut, placing the bolt in tension. The round free edge presses upward into the roof. A recessed center is lower than the outer rim (see Figure 3).

According to the patent, the new design has been found to provide the following advantages over the conventional commercial roof support device: (1) it conceals the head of the roof bolt to a preferred degree, (2) it conforms to the roof's irregularities, which causes the plate to remain tight, and (3) it compresses the lower strata of the mine roof, thereby creating a beam-like support for the upper layers of the mine roof [1].

Figure 3. Proposed design

B. *Testing*

The American Society for Testing and Materials (ASTM) designation F432, Standard Specification for Roof and Rock Bolts and Accessories, calls for specific testing of mine bearing plates. The plate is loaded with a 45 mm (1.75 inches) punch pushing downward to simulate the bolt head. An initial preload of 26.7 kN (6000 lbf) is applied. A measuring device is then set and zeroed to measure deflection in the axial direction. The punch load is increased to a total of 66.7 kN (15,000 lbf). The maximum permissible deflection between the preload and the 66.7 kN load is 3.05 mm (0.120 inches) [5].

The round mine bearing plate was designed and patented by an inventor familiar with mining but without engineering skills. Failure of the critical ASTM testing hindered the sale and use of the new design. During ASTM F432 testing, the mine bearing plate

was observed to deflect excessively during the preload phase and to buckle through at higher loads.

The problem, as presented, was to study the circular mine bearing plate design and recommend changes that would result in successful retesting.

IV. METHOD OF APPROACH

A. General Approach

Redesign of the rock bolt mine bearing plate utilized finite element analysis. Ansys, Version 9, was the program employed. The existing design was analyzed to simulate the failed testing. The model and method of approach were verified by comparison to the actual test results.

B. Model Description

The quarter model was created using Ansys Shell 43 elements. The element is a 4-node plastic large strain shell element. For this element type, the thickness is assigned as a constant. The Shell 43 element incorporates six degrees of freedom: three displacements and three rotations [6].

Because geometric and load symmetry are present, the design was analyzed as a quarter model. Symmetric boundary conditions were placed at the lines of symmetry. The plate was held vertically to simulate contact with the mine ceiling. Loads were applied as pressures over contact area of the punch from the ASTM F432 testing. This area is used by ASTM to simulate the contact area of the bolt head. The 26.7 kN (6000 lbf) preload and the 66.7 kN (15,000 lbf) were applied individually as separate load cases. Mesh refinement was done to ensure sufficient model mesh density. An element plot can be seen in Figure 4.

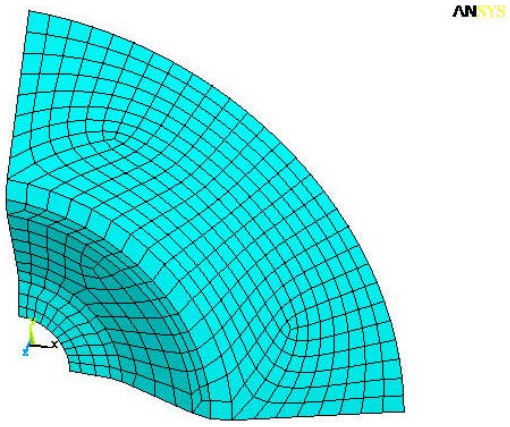

Figure 4. Ansys element plot

C. Material Description

The manufactured and tested mine bearing plate was of ASTM A-36 steel. Three grades of steel were investigated in this study: ASTM A-36, AISI 1018 CW grade 50, and AISI 1018 CW grade 70. Analysis in the plastic region of the material was necessary in order for the improved mine bearing plate to conform to the mine ceiling. The plastic region occurs when the material has been loaded beyond the yield point. Ansys requires that the true stress vs. true strain curve be input for non-linear plastic analysis.

Creation of true stress vs. true strain curves were challenging. ASTM and AISI material specifications state the minimum values permitted for the designated grade of steel. Steel manufacturers generally produce above the minimums to avoid waste. As such, stress-strain curves, created from testing, were located and modified to represent the minimum values for yield stress, ultimate stress, and modulus of elasticity. It was necessary to have the final area of the tensile specimen to determine the fracture stress and strain of the material [7]. A final area value for AISI 1018 cold worked steel was obtained from previous testing.

D. Thickness Optimization

The need for both flexibility and strength led to a thickness optimization. The thickness of the failed plate was 3.33 mm (0.131 inches). The following plate thicknesses were evaluated: 3.33 mm (0.131 inches), 5.56 mm (0.2188 inches), 6.35 mm (0.25 inches) and 12.7 mm (0.5 inches).

V. RESULTS AND ANALYSIS

A. General

Table I presents an overview of the results. The models are discussed in detail in the following sections.

B. ASTM A-36 Models

Model 36a is representative of the mine bearing plate as invented and tested. It was pressed of 3.33 mm (0.131 inches) thick, ASTM A-36 steel. The model was non-convergent due to excessive buckling for both load cases. The model failure was indicative of the actual field testing done on the part. Figure 5 is a photograph of an actual buckled bearing plate. Figure 6 is the Ansys plot of the failed part. Ansys was unable to complete the analysis due to excessive buckling. The plot shown is an intermediate point.

Table I. Overview of results

MODEL NAME	THICKNESS MM (INCHES)	LOAD KN (LBF)	MAX. DEFLECTION MM (INCHES)	MAX. STRESS KPA (KSI)
36a	3.33 (0.131)	26.7 (6,000)	buckled	buckled
		66.7 (15,000)	buckled	buckled
36b	0.556 (0.2188)	26.7 (6,000)	0.904 (0.036)	258487 (37.5)
		66.7 (15,000)	buckled	buckled
36c	0.635 (0.25)	26.7 (6,000)	0.668 (0.026)	262079 (38.0)
		66.7 (15,000)	buckled	buckled
36d	1.27 (0.5)	26.7 (6,000)	0.188 (0.007)	260472 (37.7)
		66.7 (15,000)	0.536 (0.021)	259638 (37.7)
50a	3.33 (0.131)	26.7 (6,000)	2.184 (0.086)	481395 (69.8)
		66.7 (15,000)	buckled	buckled
50b	0.556 (0.2188)	26.7 (6,000)	0.762 (0.030)	405405 (58.8)
		66.7 (15,000)	9.296 (0.366)	failed ASTM F432
50c	0.635 (0.25)	26.7 (6,000)	0.617 (0.024)	388009 (56.3)
		66.7 (15,000)	3.462 (0.136)	481354 (69.8)
50d	1.27 (0.5)	26.7 (6,000)	0.188 (0.007)	289845 (42.0)
		66.7 (15,000)	0.488 (0.019)	399924 (58.0)
70a	3.33 (0.131)	26.7 (6,000)	1.572 (0.062)	608415 (88.2)
		66.7 (15,000)	buckled	buckled
70b	0.556 (0.2188)	26.7 (6,000)	0.737 (0.029)	540010 (78.3)
		66.7 (15,000)	2.502 (0.099)	631582 (91.6)
70c	0.635 (0.25)	26.7 (6,000)	0.607 (0.024)	526123 (76.3)
		66.7 (15,000)	1.806 (0.071)	631237 (91.6)
70d	1.27 (0.5)	26.7 (6,000)	0.188 (0.007)	289845 (42.0)
		66.7 (15,000)	0.475 (0.019)	535355 (77.6)

Figure 5. Buckled plate

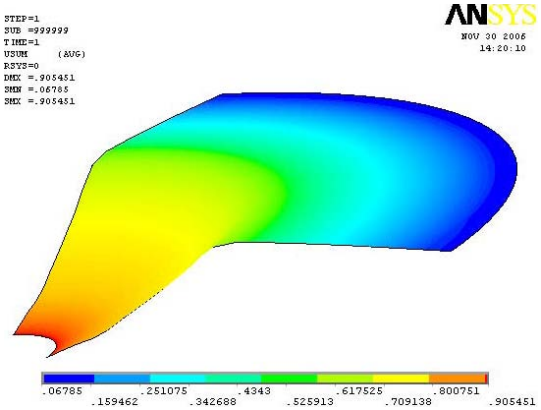

Figure 6. Model 36a buckled plate

Model 36b is representative of Model 36a with the material thickness increased to 5.56 mm (0.2188 inches). The preload values were acceptable; however, the model buckled under the 66.7 kN (15,000 lbf) load.

Model 36c is representative of Model 36a with the material thickness increased to 6.35 mm (0.25 inches). The preload deflections and stresses were acceptable; however, the model buckled under the 66.7 kN (15,000 lbf) load.

Model 36d is representative of Model 36a with the material thickness increased to 12.7 mm (0.5 inches). The stresses and deflections for both the preload and the 66.7 kN (15,000 lbf) load were acceptable. The preload and 66.7 kN load deflections were 0.188 mm (0.0074 inches) and 0.536 mm (0.0211inches) respectively. The deflection which occurred between the preload and the 66.7 kN (15,000 lbf) load was 0.348 mm (0.0137 inches). This value is well under the ASTM maximum allowable deflection of 3.05 mm (0.120 inches) [5]. The maximum Von Mises' equivalent stress, which was located at the free edge of the bolt hole for the 66.7 kN (15,000 lbf) load, was 259,638 kPa (37,656 psi).

C. AISI 1018, Grade 50 Models

The results for the AISI 1018, 50 grade steel mine bearing plates can be seen in Table I.

Model 50a is representative of Model 36a with a material change to grade 50 steel. It has a thickness of 3.33 mm (0.131 inches). The deflection difference seen for both loads indicates that buckling occurred.

Model 50b is representative of Model 50a with the material thickness increased to 5.56 mm (0.2188 inches); the steel was AISI 1018 CW. The design failed to meet the deflection criteria of ASTM F432.

Model 50c is representative of Model 50a with the material thickness increased to 6.35 mm (0.25 inches). The preload and 66.7 kN load deflections were 0.188 mm (0.0074 inches) and 0.536 mm (0.0211inches) respectively. The deflection difference which occurred between the preload and the 66.7 kN (15,000 lbf) load was 2.845 mm (0.112 inches), which is below the ASTM maximum deflection of 3.05 mm (0.120 inches) [5]. The maximum Von Mises' equivalent stress for the 66.7 kN (15,000 lbf) load was 481,354 kPa (69.8 ksi). The location of maximum stress was at the free edge of the bolt hole.

Model 50d is representative of Model 50a with the material thickness increased to 12.7 mm (0.5 inches). The stresses and deflections for both the preload and the 66.7 kN (15,000 lbf) load were acceptable. The preload and 66.7 kN load deflections were 0.617 mm (0.0243 inches) and 0.488 mm (0.0192 inches) respectively. The deflection difference was 0.130 mm (0.0051 inches), which is under the ASTM maximum deflection of 3.05 mm (0.120 inches) [5]. The maximum Von Mises' equivalent stress for the 66.7 kN (15,000 lbf) load was 399,924 kPa (58.0 ksi).

D. AISI 1018, Grade 70 Models

The results for the AISI 1018, 70 grade steel mine bearing plates can be seen in Table I.

Model 70a is representative of Model 36a with a material change to AISI, 70 grade steel. It has a thickness of 3.33 mm (0.131 inches). The deflection difference between the preload and the 66.7 kN (15,000 lbf) load failed the ASTM Designation F432 criteria and indicated that mild buckling occurred.

Model 70b is representative of Model 70a with the material thickness increased to 5.56 mm (0.2188 inches). The deflections were 0.736 mm (0.0290 inches) and 2.450 mm (0.0964 inches) for load cases 1 and 2, respectively. The change in deflection between the preload and the 66.7 kN (15,000 lbf) load was 1.714 mm (0.0674 inches), which meets the requirements of ASTM F432. The maximum Von Mises' equivalent stress for the 66.7 kN (15,000 lbf) load was 631,582 kPa (91.6 ksi). The location of the maximum stress, as expected, was at the free edge of the bolt hole.

Model 70c is representative of Model 70b with the material thickness increased to 6.35 mm (0.25 inches). The preload and 66.7 kN load deflections were 0.607 mm (0.024 inches) and 1.806 mm (0.071inches) respectively. The deflection difference, which occurred between the preload and the 66.7 kN (15,000 lbf) load, was 1.199 mm (0.047 inches), which meets the ASTM requirement of 3.05 mm (0.120 inches) [5]. The maximum Von Mises' equivalent stress for the 66.7 kN (15,000 lbf) load was 631,237 kPa (42.0 ksi). The location of maximum stress was at the edge of the bolt hole.

Model 70d is representative of Model 70c with the material thickness increased to 12.7 mm (0.5 inches). The stresses and deflections for both the preload and the 66.7 kN (15,000 lbf) load were acceptable. The preload and 66.7 kN load deflections were 0.188 mm (0.007 inches) and 0.475 mm (0.019 inches) respectively. The deflection difference was 0.287 mm (0.011inches), which is under the ASTM maximum of 3.05 mm (0.120 inches) [5]. The maximum Von Mises' equivalent stress for the 66.7 kN (15,000 lbf) load was 535,355 kPa (77.6 ksi).

VI. RECOMMENDATIONS

Further consideration was not given to models that buckled or exceeded the ASTM deflection criteria. Other variables for consideration were product cost, manufacturing, and handling of the rock bolt mine bearing plate. The optimized design was Model 70b, based on the aforementioned. Model 70b suggests a plate designed of AISI 1018 CW grade 70 steel with a thickness of 5.56 mm (0.2188 inches). All other models that passed the ASTM Designation F432 criteria were heavier sections.

The deflection criterion was met for Model 70b as shown in Figure 7. Figure 8 shows that the maximum stress value, 631,582 kPa (91.6 ksi), was above the 482,650 kPa (70.0 ksi) yield strength of the material, indicating that the plate will conform to the mine roof. Next, the maximum stress of the part was compared to the failure strength of the

material to ensure that the part was not nearing the limits of ductility. Tensile testing of the material resulted in a failure strength of 691,569 kPa (100.3 ksi). The stress vs. strain curve is shown in Figure 9. It was determined that 8.67% of the material ductility remains as a safety factor for the design.

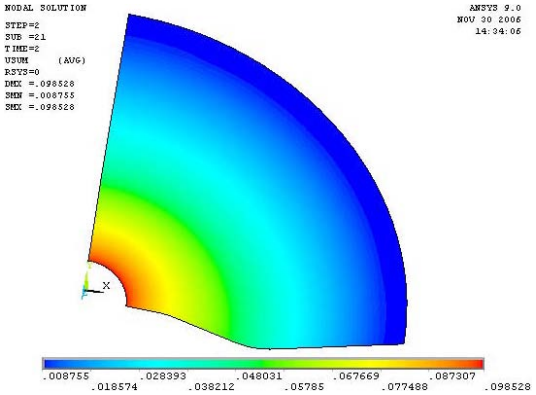

Figure 7. Model 70b maximum deflection

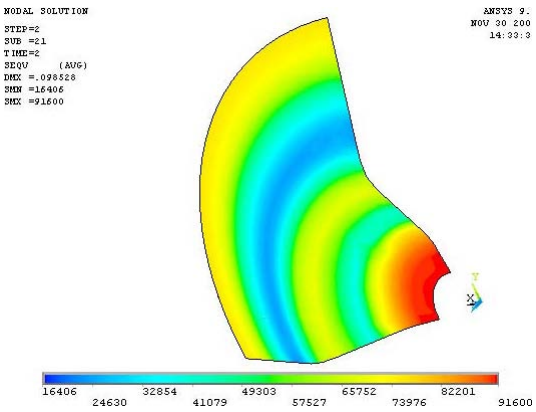

Figure 8. Model 70b maximum Von Mises stress

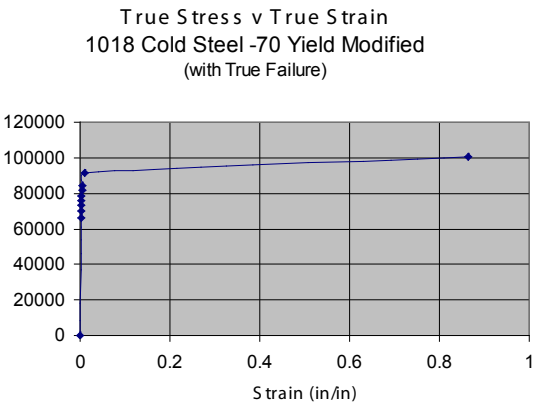

Figure 9. AISI 1018 CW grade 70 stress vs. strain curve

VII. CONCLUSION

Mine bearing plates are an integral part of underground mine ceiling structures. Currently used designs have several drawbacks that have been addressed with a newly patented design. The improved rock bolt mine bearing plate required the use of stress analysis in the materials plastic region of the stress-strain curve. The results of extensive finite element analysis indicate that, for the criteria given, the plate should be made of AISI 1018 CW grade 70 steel with a thickness of 5.56 mm (0.2188 inches). Actual testing is recommended to further verify the analysis.

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