Advancing Paste Fill Bulkhead Design Using Numerical Modeling

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ABSTRACT: Bulkhead failure is a core geotechnical risk that is an inherent feature of any mining method employing paste or hydraulic fill. Historically within Australia the design of bulkheads has relied on simplified analytical solutions. Three-dimensional numerical modeling provides a method to explicitly model the actual bulkhead geometry, bulkhead construction materials and wall-rock interface. In 2005/06 a collaborative project involving six Australian paste and hydraulic fill operations using sprayed Fibrecrete/Shotcrete/Aquacrete bulkheads was conducted. This paper presents the findings of this study. Topics described include review of currently used analytical bulkhead design methods and their limitations, a description of the FLAC3D Shotcrete Bulkhead Model, comparison of the numerical model results with common analytical solutions, and verification of the modeling methodology against actual bulkhead failures.

1. INTRODUCTION

Paste fill is being employed increasingly in underground metalliferous mines where, traditionally, hydraulic fill has been used as a passive support element. One advantage of paste fill as opposed to hydraulic fill is its non-segregating nature, whereby negligible excess water is produced when the fill is stationary. This eliminates the need for permeable barricades that are required to drain the transport water from a hydraulic fill mass. In this paper "bulkhead" refers to an impermeable (water retaining) structure; systems may be established to drain water from behind such bulkheads. "Barricade" refers to a permeable free draining structure. However, it should be noted that within Australia the terms "bulkhead" and "barricade" are used interchangeably to describe both draining and non-draining structures that contain paste fill within stopes.

The design of paste fill bulkheads throughout the industry currently relies upon simplified analytical solutions. These solutions are limited severely by the necessary simplification of geometry, the properties of the bulkhead materials and the representation of the wall-bulkhead interface. Three-dimensional numerical modelling provides a means to explicitly model the actual bulkhead geometry and material properties, along with the loading condition applied by a paste fill mass.

2. BACKGROUND

Upon hydration of the cement within paste fill, arching of the fill into the stope and drive walls reduces the active pressure applied to bulkheads at the base of a stope. Paste fill bulkheads, therefore, can be designed to be of lower strength and lower cost than those required for traditional hydraulic fill applications. Although paste fill bulkheads pose a lower risk of hazardous inrush than those required for hydraulic fill, a thorough understanding of the imposed loads and failure mechanisms of paste fill bulkheads is required for mine operators to balance strength and safety against cost and practicality.

The most commonly used paste fill bulkhead designs throughout Australia and North America are listed below. They include:

- Sprayed shotcrete or fibrecrete,

- Sprayed Aquacrete,
- Mullock pile sprayed with shotcrete, and
- Hybrid mullock pile and shotcrete,

Figure 1 illustrates a typical fibrecrete bulkhead.

Fig. 1. Typical sprayed shotcrete/fibrecrete paste bulkhead.

3. TRADITIONAL BULKHEAD DESIGN METHODS

Several analytical design methods have been developed to estimate the strength of fill retaining bulkheads. The main design methods are discussed below.

3.1. Structural Design Based Upon American Concrete Institute (ACI) Code

The structural design of bulkheads in accordance with the allowable moment, shear and normal loads provided by building codes, for reinforced concrete civil structures, has been applied at several paste fill operations. Often a linear-elastic, simply supported two-dimensional beam is simulated with a finite element model to determine the maximum bulkhead loads. Djahanguiri and Abel (1997) describe the structural design of reinforced impermeable bulkheads used for underground leaching of uranium ore at the Edgar Mine in Colorado. Simple two-dimensional beam theory solutions were used to determine the loads imposed on a 0.305 m thick, 2.7 m high, 3.0 m wide bulkhead. Steel reinforcement was designed based upon the ACI code allowable limits for plain concrete and steel-reinforced concrete structures.

Due to the assumptions imposed when a two-dimensional, simply supported beam is used to simulate a three-dimensional partially clamped bulkhead, the structural design of paste bulkheads using building code limits generally results in an overly conservative design.

3.2. Analytical Design of Concrete Bulkheads

Smith and Mitchell (1982) provide simple analytical solutions for the design of impermeable concrete bulkheads. These solutions use a shear resistance and maximum bending moment to determine the required bulkhead thickness. This approach has generally been found to result in overly conservative bulkhead designs.

3.3. Yield Line Theory

Yield line equations have been developed to estimate the ultimate load of reinforced concrete slabs (Jones, 1967; Johansen, 1972). The ultimate load of the slab system is estimated by postulating a collapse mechanism compatible with the slab boundary conditions and plastic hinge lines. The moments at the plastic hinge lines are the ultimate moments of resistance of the slab sections (defined directly with reference to reinforcing steel and the concrete). The ultimate load is determined using the principle of virtual work or equations of equilibrium, assuming a flexural mode of failure and perfect plasticity. Figure 2 illustrates the yield line pattern assumed for a simply supported square slab. Yield line theory assumes a flexural collapse mode — that is, that the slab has sufficient shear strength to prevent shear failure.
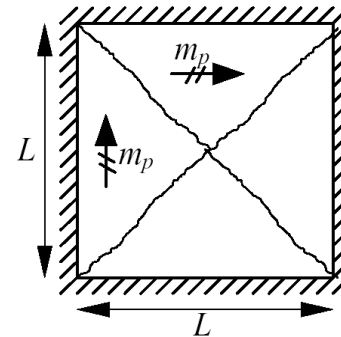

Fig. 2. Yield line pattern assumed for a simply supported square slab.

Some relations between the ultimate uniformly distributed load (w_p) and ultimate positive moment of resistance (m_p) for a square slab that have been obtained by yield line analysis for different slab boundary conditions are presented in Table 1. The yield line method of analysis, which conforms to the American and British building codes of practice, is a robust tool for the analysis of reinforced concrete slabs. In its standard form, however, the method is not able to account for membrane

(arching) forces that are mobilized at the slab edges. Timoshenko and Young (1972) suggest that the ultimate moment of resistance per unit width L is:

$$m_p = \frac{h^2}{4}\sigma_t \quad (1)$$

where:

h = plate thickness, and

σ_t = tensile strength

Table 1. Sample tables with values.

Case	Equation
All edges simply supported	$w_p = \dfrac{24m_p}{L^2}$
All edges fully fixed	$w_p = \dfrac{48m_p}{L^2}$
Top and bottom edges fully clamped, left and right sides simply supported	$w_p = \dfrac{35.44m_p}{L^2}$
Lower edge simply supported, others are fully fixed	$w_p = \dfrac{41.36m_p}{L^2}$
Lower edge fixed, other three simply supported	$w_p = \dfrac{29.9m_p}{L^2}$

Experience from the structural engineering industry (Powell, 1956; Niblock, 1986; Wood, 1961) indicates that the yield line method does not accurately determine the failure load of reinforced concrete slabs under all loading and support conditions. In cases where the slab is at least partially clamped, the yield line method provides a conservative estimate of the ultimate failure pressure. Famiyesin et al. (2001) suggest that numerical modelling remains the most accurate tool for predicting the ultimate load of reinforced concrete slabs, as it incorporates both the geometric and material nonlinearities of a slab.

3.4. Current Australian Shotcrete Bulkhead Yield-Line Design (Beer, 1986)

The current methodology that is used to design shotcrete bulkheads at many Australian paste fill operations is based upon a form of yield line theory. Figure 3 illustrates the ultimate strength calculator that is used at many Australian paste fill operations.

Simplified Slab Formula for [square] barricade strength estimation
Using Yield Line theory of concrete technology
Assumes that bulkhead has cracked in tension along diagonal lines and along the bulkhead rock interface

			Where			Values
$w_p = \dfrac{24\,m_p}{b^2}$			Compressive strength of mortar	σ_c	MPa	11.0
			dimension	b	m	4.0
			thickness	h	m	0.46
			Plastic moment	m_p	MNm/m	0.291
$m_p = \sigma_c\,\dfrac{h^2}{8}$			Pressure at Failure	w_p	**MPa**	**0.436**

*One masonry wall of these dimensions and properties tested to destruction failed at 750 kPa
Implied safety factor = **1.72**

Fig. 3. Current Australian Bulkhead Yield-Line Design.

Although the formula is routinely used to determine the ultimate strength of shotcrete bulkheads, the original solution was proposed by Beer (1986) to estimate the ultimate strength of a masonry bulkhead.

It is believed that the yield line solution proposed by Beer (1986) has been adapted from an unknown masonry wall yield-line solution, as Beer states that the solution is based upon "simplified" theory. Although Beer states that the formula assumes that the bulkhead has cracked in tension along the bulkhead–rock interface, the expression used to calculate the ultimate pressure at failure (w_p) is for a slab with simply supported edges (Table 1). Beer originally proposed the simplified solution to back-analyse the failure pressure of a $4 \times 4 \times 0.46$ m square concrete masonry bulkhead that cracked extensively at 750 kPa during a controlled experiment at the Mt. Isa Mine (Figure 4). Assuming a mortar compressive strength of 11 MPa, the estimated failure pressure is 0.436 MPa. This is 1.72 times lower than the actual failure pressure.

Fig. 4. Masonry bulkhead pressurized to 750 kPa at the Mt. Isa Mine (Grice, 1989)

Although crack patterns observed in masonry walls are similar to yield line patterns observed in reinforced concrete slabs, several researchers have pointed out that there is no theoretical basis for applying yield line theory to an unreinforced masonry wall (Hendry, 1981; Martini, 1997; Sinha, 1978). A particular problem applying a yield line solution to a masonry wall is the orthotropic nature of masonry structures. This is observed clearly in the failure pattern illustrated in Figure 4.

4. NUMERICAL MODELLING OF SPRAYED SHOTCRETE PASTE BULKHEADS

A calibrated three-dimensional numerical modelling approach has been proposed as the most appropriate method of paste fill bulkhead design (Bridges, 2003). A three-dimensional numerical model can be developed to incorporate realistic bulkhead shapes, non-linear material properties and an interface between the bulkhead and wall rock. However, there still remains a substantial amount of uncertainty in simulating representative bulkhead material properties and loading conditions.

4.1. Modelling Methodology

The three-dimensional numerical modelling code FLAC3D (Itasca, 2005) was used to model the uniform loading of shotcrete bulkhead structures. FLAC3D allows the specification of complex strain-softening material models to simulate brittle shotcrete behaviour, together with sliding interfaces to represent the shotcrete–wall rock interface. The explicit large-strain formulation allows the full failure mechanism of a bulkhead to be analysed. The FLAC3D Shotcrete Bulkhead Model is used to describe the bulkhead modelling methodology within this report.

4.2. Model Geometry

Two main bulkhead geometries were investigated throughout the study; they include a 5 × 5 m square bulkhead and a 5 × 5 m horseshoe bulkhead. An arched profile with a radius of curvature of 6.5 m was also investigated for the horseshoe geometry, as illustrated in Figure 5.
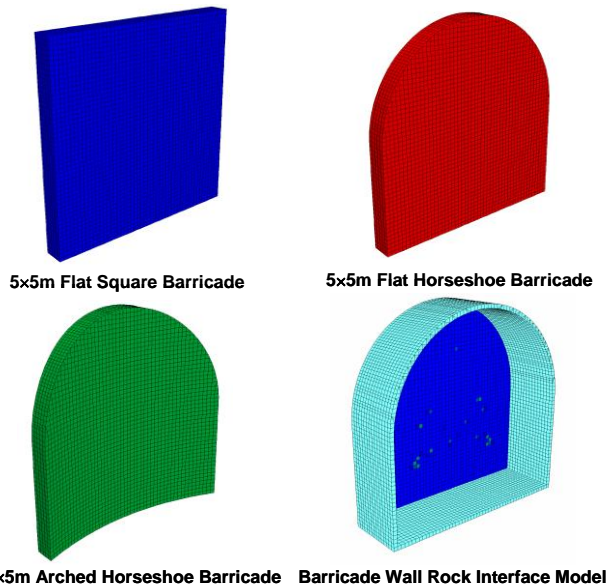

5×5m Flat Square Barricade   5×5m Flat Horseshoe Barricade

5×5m Arched Horseshoe Barricade   Barricade Wall Rock Interface Model

Fig. 5. Bulkhead shapes investigated throughout the study.

4.3. Shotcrete/Fibrecrete Material Properties

For the purpose of initial testing and verification of the FLAC3D Shotcrete Bulkhead Model, a shotcrete material with an unconfined compressive strength (UCS) of 30 MPa was selected. The material properties presented in Table 2 were selected based upon shotcrete characterization conducted by Thomas et al. (2001).

Table 2. Material properties used to simulate the behaviour of 30 MPa UCS shotcrete.

σ_c (MPa)	$E^{\#}$ (GPa)	v	c_p^{*} (MPa)	c_r (MPa)	ϕ_p (°)	ϕ_r (°)	$\sigma_{tp}^{\#\#}$ (MPa)	σ_{tr} (MPa)
30	25	0.2	7.5	0.0	37	32	2.9	0.0

$$^{\#} E = 4570\sqrt{\sigma_c} \text{ (Macgregor, 1997)} \tag{2}$$

$$^{*} \sigma_c = \frac{2c \times \cos(\phi)}{1 - \sin(\phi)} \tag{3}$$

$$^{\#\#} \sigma_t = 0.3 \times \sigma_c^{0.67} \text{ (Thomas et al., 2001)} \tag{4}$$

The specification of ductile or brittle behaviour in a numerical model is a very important consideration, as brittle materials tend to undergo progressive collapse much sooner after yielding begins. Ductile materials, on the other hand, are likely to remain stable well after yielding begins. For this reason, a Mohr-Coulomb strain-softening model, which simulates the actual post-peak strength degradation, has been used to represent the behaviour of shotcrete upon loading.

In order to simulate the strain-softening behaviour of shotcrete, the decrease in strength as a function of the plastic strain (εps) accumulated in the yielding material needs to be described explicitly. For the purpose of this study, it was assumed that the cohesion and tensile strength would decrease linearly from their maximum value at zero plastic strain, down to zero at a critical plastic strain (εps$_{crit}$) value. The critical plastic strain required to simulate the post-peak behaviour of shotcrete was determined by simulating a UCS test within FLAC3D. Figure 6 illustrates the stress-strain response of 30 MPa shotcrete material from the numerical UCS tests conducted using the Mohr Coulomb strain-softening modelling methodology. As observed, the modelling methodology causes localization along shear bands whereby the cohesion of the shotcrete material has degraded from the intact value to zero. This is the same behaviour observed in physical UCS tests on concrete.

The critical strain used to generate the brittle behaviour observed in Figure 6 is 0.06 for a zone size of 1 m. This critical strain value was obtained from a back-analysis of concrete tunnel-liner performance at the Wesselton and Premier Mines (Lorig and Pierce, 2000).
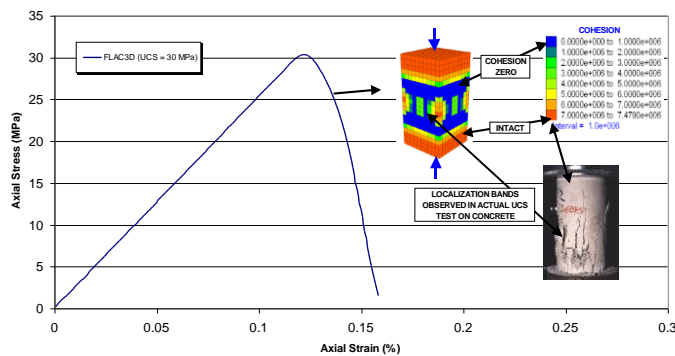

Fig. 6. Stress-strain curve obtained from numerical UCS test.

The addition of fibre reinforcement has a significant impact on the ability of the composite material to carry load in flexure beyond the flexural capacity of the shotcrete itself. An increased volume of fibre results in increased ductility or "toughness" of the fibrecrete. The post-peak flexural capacity of fibrecrete can be determined through a variety of internationally recognized methods. The Flexural Toughness of Fiber Reinforced Concrete (Round Panel) Test (ASTM: C 1500-04) has been simulated within FLAC3D to calibrate the post-peak flexural behaviour of fibrecrete. Figure 7 illustrates the typical failure mechanism developed during a Round Panel Test.
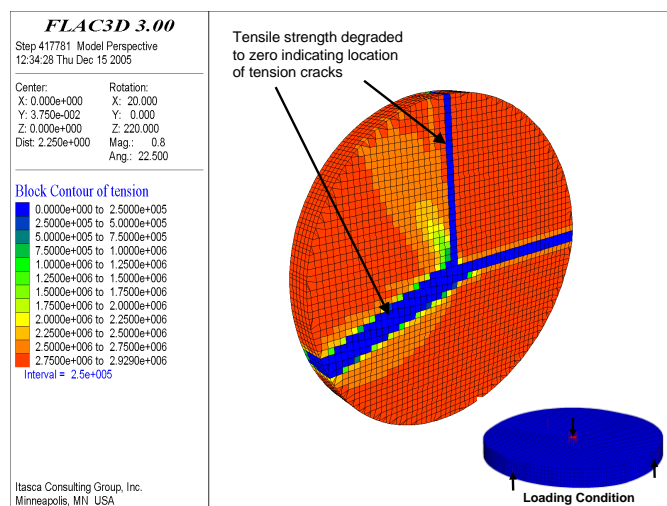
Fig. 7. Failure mechanism developed during flexural toughness test.

The tension-softening rate controls how quickly the tensile strength degrades with increasing strain.

This controls the fibrecrete toughness, which is related directly to the type and dosage of fibres within the fibrecrete. In order to simulate different levels of fibre reinforcement, different tension-softening rates can be implemented within FLAC3D, as illustrated in Figure 8.
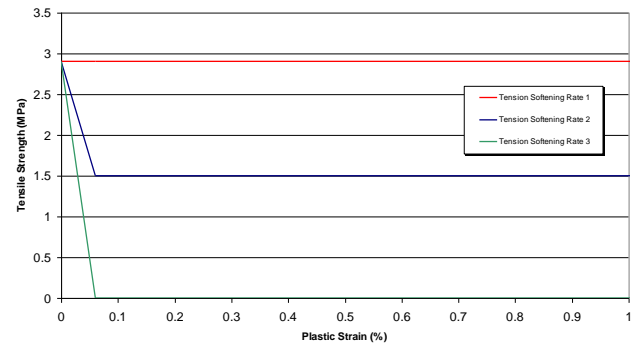

Fig. 8. Tension-softening rates simulated.

The corresponding load-deflection curve from each simulated Round Panel Test is illustrated in Figure 9. As observed, the methodology adopted to simulate different levels of fibre reinforcement within FLAC3D can simulate the post-peak flexural behaviour of fibrecrete accurately. For the purpose of initial testing and verification of the FLAC3D Shotcrete Bulkhead Model, tension-softening rate 3 was used to simulate the post-peak flexural behaviour of the bulkhead material.
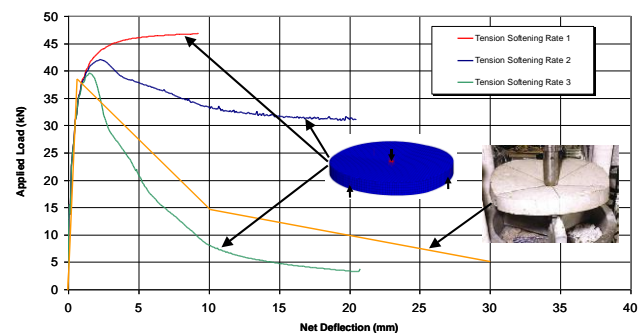

Fig. 9. Simulated load-deflection curves for each tension-softening rate.

Wire mesh reinforcement has not been included in the model. Typically during construction of sprayed shotcrete bulkheads, wire mesh is used as formwork rather than a reinforcing element. It is not known whether wire mesh placed on one side of a bulkhead as formwork provides any bending resistance to the bulkhead.

Detailed geomechanical laboratory testing of site-specific shotcrete and fibrecrete materials is required to provide confidence in the predicted behaviour of paste bulkheads.

4.4. Strength and Stiffness of Shotcrete–Wall Rock Interfaces

A series of laboratory tests was conducted by Saiang et al. (2005) to determine the strength and stiffness of the interface between shotcrete and a rock surface. Direct shear tests and direct tension tests of shotcrete-rock samples were conducted. Two rock types were selected for direct shear testing: (1) magnetite samples with registered Joint Roughness Condition (JRC) values between 1 to 3; and (2) trachyte samples with registered JRC values between 9 and 13.

The compressive strength of the shotcrete used throughout the direct shear and tension tests was measured to be 56.3 MPa after 50 days. A summary of the shear strength and tensile strength test results is presented in Table 3.

Table 3. Summary of shear and tension tests (after, Saiang et al., 2005).

	JRC 1- 3	JRC 9-13
K_s (MPa/mm)	0.94	1.3
c_{peak} (MPa)	0.25	0.5
$c_{residual}$ (MPa)	0.03	0.08
ϕ_{peak} (°)	40	47
$\phi_{residual}$ (°)	35	39
σ_t (MPa)	0.56	0.56

For the purpose of initial testing and verification of the FLAC3D Shotcrete Bulkhead Model, the wall rock material was assumed to act as an intact elastic rock material.

5. FLAC3D SHOTCRETE BULKHEAD MODEL RESULTS

5.1. Comparison of FLAC3D Shotcrete Bulkhead Model to Yield Line Theory

A square 5 × 5 m bulkhead of varying thickness, with 30 MPa UCS shotcrete, was selected as a base case model to compare the FLAC3D Shotcrete Bulkhead Model to the following two analytical methods:

(a) the standard yield-line theory solution (Johansen, 1972) for a simply supported concrete slab that is used throughout the concrete industry to design reinforced concrete slabs; and

(b) the yield line solution proposed by Beer (1986) for permeable concrete brick bulkheads, which has been adopted widely throughout the Australian paste fill industry for the design of sprayed shotcrete/fibrecrete bulkheads.

The analytical solutions used for comparison are presented in Table 4.

Table 4. Analytical solutions to used compare FLAC3D model results.

Case	Equation
All edges simply supported (Johansen, 1972)	$w_p = \dfrac{6 \times \sigma_t \times h^2}{L^2}$
All edges fully fixed (Johansen, 1972)	$w_p = \dfrac{12 \times \sigma_t \times h^2}{L^2}$
Industry standard method (Beer, 1986)	$w_p = \dfrac{3 \times \sigma_c \times h^2}{L^2}$

where:

$W_p =$ ultimate failure pressure,

$\sigma_t =$ shotcrete tensile strength,

$\sigma =$ mortar compressive strength,

$h =$ bulkhead thickness, and

$L =$ bulkhead width / height.

Figure 10 illustrates the failure mechanism and load-displacement curve of a simply supported 5 × 5 × 0.5 m square bulkhead. Localized tension-softening bands are observed to develop diagonally across the bulkhead, indicating the location of tension cracks. Corner levers are predicted to develop at the corners of the slab.

Macgregor (1997) suggests that, as a result of bending, the yield line patterns in the corners of simply supported slabs fork out to the sides of the slab. If the corner is held down, a crack will form across the corner as, illustrated in Figure 11.
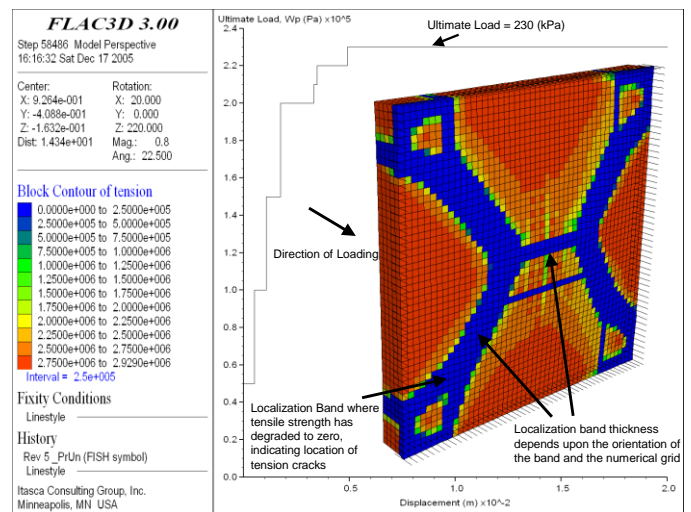

Fig. 10. Failure mechanism and load-displacement curve of a simply supported 5 × 5 × 0.5 m square bulkhead.

Localized softening bands should be used only as an indication of the controlling failure mechanism. Although the overall physics of band formation is

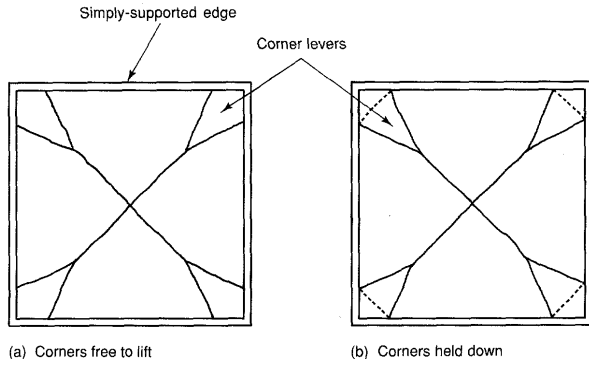modelled correctly by FLAC3D, band thickness and spacing are grid-dependant.

Fig. 11. Corner levers in simply supported slabs (Macgregor, 1997).

Figure 12 illustrates the predicted ultimate load for a simply supported 5 × 5 m square, 30 MPa shotcrete bulkhead with thicknesses of 0.2, 0.3, 0.4, 0.5, 0.8 and 1.2 m. The modelling results are compared to the two analytical methods of Johansen (1972) and Beer (1986).

The FLAC3D modelling results provide an exact match to the standard, simply supported yield-line solution (Johansen, 1972). However, the ultimate load predicted by both the FLAC3D results and the standard simply supported yield-line solution (Johansen, 1972) is significantly lower than the ultimate load predicted by the yield-line solution proposed by Beer (1986).
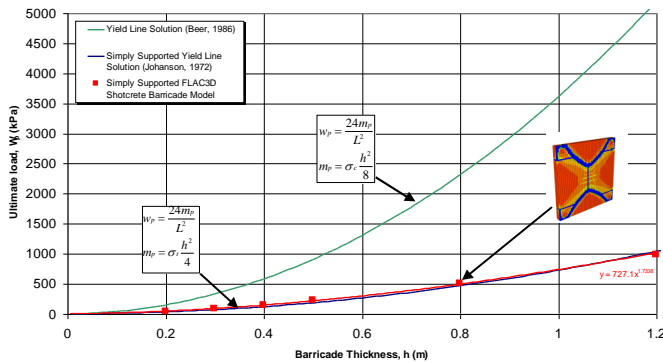
Fig. 12. Ultimate bulkhead load for a simply supported 5 × 5 m square, 30 MPa shotcrete bulkhead.

Figure 13 illustrates the predicted ultimate load for a fully fixed (clamped) 5 × 5 m square, 30 MPa shotcrete bulkhead with thicknesses of 0.2, 0.3, 0.4, 0.5, 0.8 and 1.2 m. The FLAC3D modelling results predict ultimate loads significantly greater than both the standard fully fixed yield-line solution used throughout the concrete industry (Johansen, 1972) and the yield solution proposed by Beer (1986). For a bulkhead thickness between 0.2 and 0.5 m, the

FLAC3D results provide a close correlation to the calibrated yield-line solution proposed by Beer (1986), whereby the basic solution is multiplied by a factor of 1.72. This is the same factor used to calibrate the solution to failure of a masonry bulkhead at Mt. Isa.
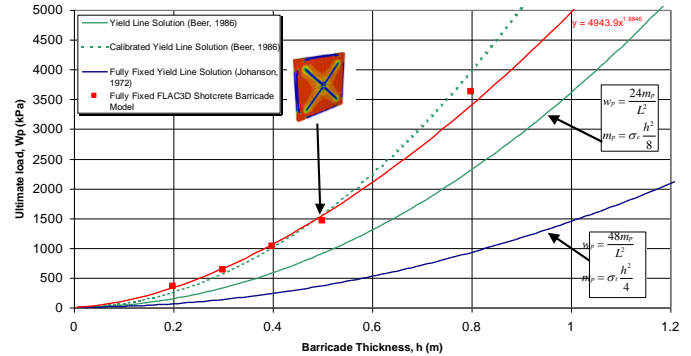

Fig. 13. Ultimate load for fully fixed 5 × 5 m square, 30 MPa shotcrete bulkhead.

Physical experiments conducted on fully clamped reinforced concrete slabs (Niblock, 1986) demonstrate the conservative nature of fully clamped yield-line solutions that do not consider the compressive membrane action which results in internal arching within a fully clamped slab, or bulkhead. Figure 14 illustrates the displacement profile at the edge of a simply supported and fully fixed bulkhead. As observed, the simply supported bulkhead is free to rotate, as no horizontal restraint is provided. Together with horizontal restraint, the fully fixed boundary condition causes a bending moment about the bulkhead boundary.
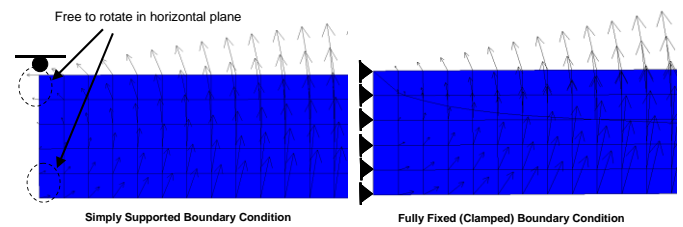

Fig. 14. Displacement profile for a simply supported and fully fixed square bulkhead.

5.2. Affect of Bulkhead–Wall Rock Shear Interface

A square 5 × 5 m bulkhead of varying thickness was selected to compare the FLAC3D Shotcrete Bulkhead Model with a sliding interface to simulate the bulkhead–wall rock contact to a simple analytical solution for shear resistance along a four-sided block. Bulkheads with a thickness of 0.3, 0.4, 0.5, 0.8 and 1.2 m were analysed. Figure 15 illustrates the perfect correlation between FLAC3D model and the simple analytical solution.

A sliding interface boundary condition was added to a square 5 × 5 m bulkhead to simulate the coupled behaviour of both the bending and shear failure mechanisms. The wall rock material was assumed to have a joint roughness condition of between 1-3, as described by Saiang et al. (2005).
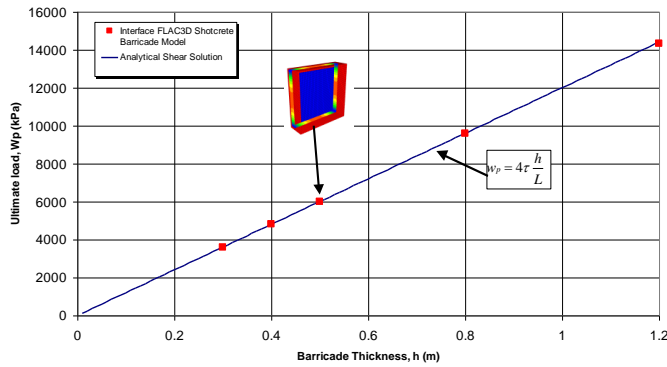

Fig. 15. Ultimate shear load for a 5 × 5 m square, 30 MPa shotcrete bulkhead.

Figure 16 illustrates the ultimate load predicted for a 0.5 m and 0.8 m thick bulkhead with a shear-interface boundary condition.
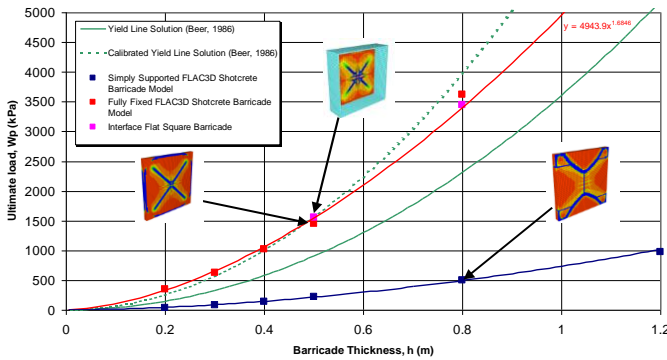

Fig. 16. Ultimate load for a simply supported, fully fixed and shear interface 5 × 5 m square, 30 MPa shotcrete bulkhead.

Figure 17 illustrates the failure mechanism of a bulkhead with a shear interface at the bulkhead wall rock boundary. Bending of the bulkhead material causes rotation and high normal stress at the front edge of the bulkhead. This high normal stress prevents sliding along the interface, eventually leading to shear/compression failure at the front edge and separation at the back edge of the bulkhead-wall rock interface. Failure at the front edge of the bulkhead reduces the moment carrying capacity of the bulkhead, leading to increased bending and then localized tension failure on the front face and compression failure on the back face of the bulkhead. The shear-interface boundary condition provides a more realistic representation of the actual bulkhead–wall rock system than the simply supported and fully fixed boundary conditions assumed in the analytical solutions for bulkhead design.
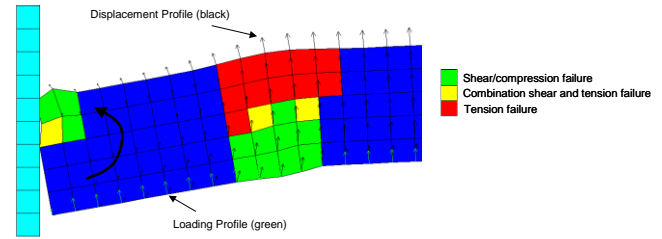

Fig. 17. Failure mechanism of bulkhead with a shear interface boundary condition.

5.3. Affect of Bulkhead Geometry and Bulkhead Arching

A 5 × 5 m flat horseshoe-shaped bulkhead of varying thickness, with 30 MPa UCS shotcrete, was constructed to simulate a typical bulkhead shape constructed *in situ*. Bulkheads with a thickness of 0.3, 0.4, 0.5 and 0.8 m were analysed. Figure 18 illustrates the ultimate load predicted for a fully fixed and simply supported flat horseshoe bulkhead compared to a square bulkhead. For the fully fixed boundary condition, the horseshoe shape results in a slightly higher ultimate load than the square bulkhead shape.
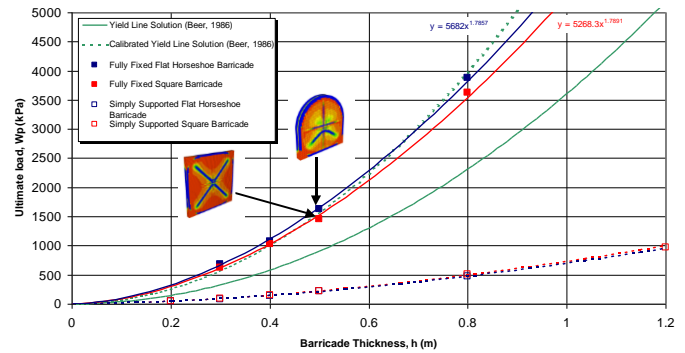

Fig. 18. Ultimate load for simply supported and fully fixed 5 × 5 m square and horseshoe, 30 MPa shotcrete bulkheads.

A separate model was constructed to simulate a 5 × 5 m horseshoe-shaped bulkhead with an arched face (radius of curvature of 6.5 m). Figure 19 illustrates the ultimate load predicted for the arched face bulkhead compared to the flat horseshoe bulkheads with a shear interface boundary condition.

Due to the arched shape of the bulkhead, all forces within the bulkhead remain in compression, while bending of the arched bulkhead generates a thrust at the wall abutments, as illustrated in Figure 20. This results in a higher ultimate load for the same flat bulkhead thickness.
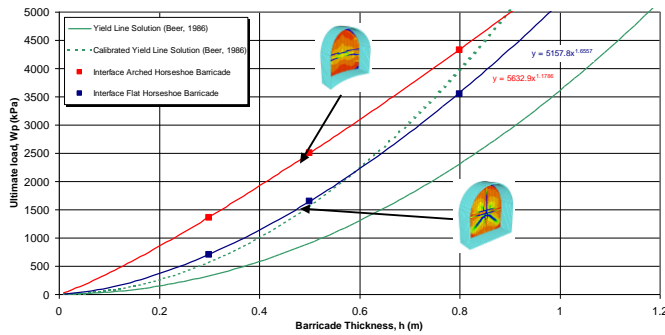
Fig. 19. Ultimate load for shear interface 5 × 5 m flat horseshoe and arched horseshoe, 30 MPa shotcrete bulkheads.
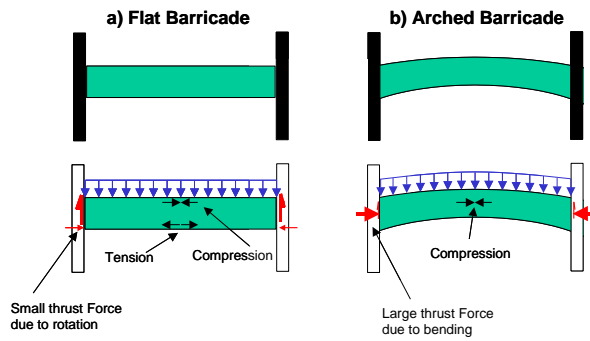

Fig. 20. Forces within a flat and arched bulkhead.

6. VERIFICATION OF FLAC3D SHOTCRETE BULKHEAD MODEL

In order to gain confidence in the predicted failure pressure and failure mechanism of the shotcrete bulkhead model, the FLAC3D Shotcrete Bulkhead Model has been compared to physical experiments conducted on similar structures.

6.1. Pressure Testing of Bulkheads at the Gaspe Mine

During late 1990 and early 1991, Noranda Technology Centre (NTC) pressurized two timber-reinforced bulkheads at the Gaspe Mine (Miller et al., 1991). Both tests consisted of a 3 × 3.5 × 1.8 m bulkhead constructed with "Tekfoam" foamed cement, which has a uniaxial compressive strength of approximately 137 kPa. In both cases, failure is observed to occur at the bulkhead–wall rock interface. The failure pressure of Test 1, conducted on November 6, 1990, was 124 kPa, while Test 2, conducted on May 23, 1991 achieved a failure pressure of 165 kPa. A representative bulkhead model was constructed within FLAC3D to compare the predicted and observed failure conditions.

Figure 21 illustrates the predicted failure pressure and failure mechanism of the FLAC3D model compared to the actual bulkhead behaviour. As observed, the predicted failure pressure is consistent with the measured pressure during the two *in situ*

tests. As observed *in situ*, yielding is predicted to propagate from the bulkhead–wall rock contact.
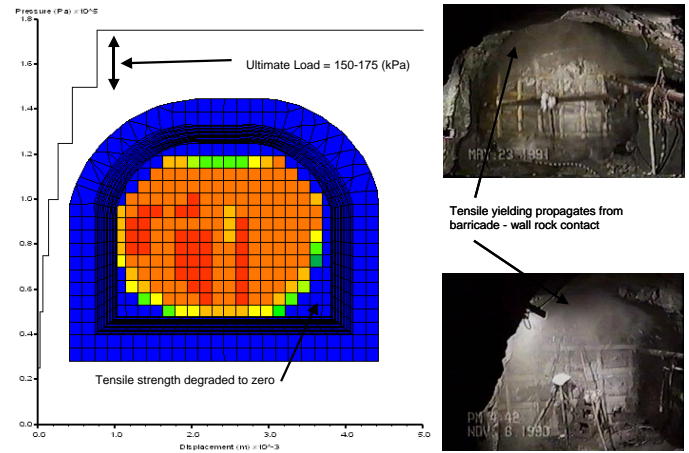

Figure 21. Failure pressure and failure mechanism predicted with FLAC3D compared to in situ pressure tests conducted at the Gaspe Mine (after, Miller et al., 1991).

6.2. Back-Analysis of Sprayed Aquacrete Paste Bulkhead Failure

A paste bulkhead failure occurred at an Australian paste fill operation during 2006. After filling for approximately 2.5 hours, the sprayed Aquacrete paste bulkhead at the base of the stope failed catastrophically, and paste fill within the stope flowed into ore drive. At the time of failure, the height of the paste fill was estimated to be 6.5 to 7 m high. Because the paste fill had not undergone any significant hydration at the time of failure, the load applied to the bulkhead is simply the hydraulic pressure caused by the height of the paste fill. For a 7 m fill height, this equates to a horizontal pressure of 132 kPa at the base of the bulkhead. Figure 22 illustrates the ultimate failure load and failure mechanism of a 5 MPa Aquacrete bulkhead. Failure of the bulkhead can be observed to propagate from the base of the bulkhead when the maximum load (at the base) reaches 130 kPa.
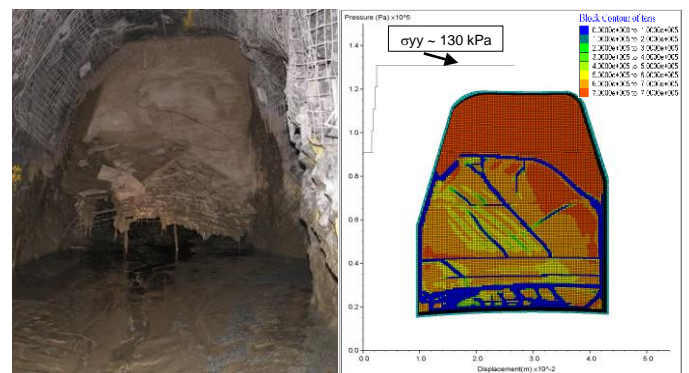

Fig. 22. Ultimate load and failure mechanism of 5 MPa Aquacrete bulkhead.

7. CONCLUSIONS

The FLAC3D Shotcrete Bulkhead Model provides a sound technical basis for the design of paste fill retaining bulkheads. The model results of a simply supported 5 × 5 m square bulkhead provide a perfect correlation with the yield line solution for a simply supported concrete slab (Johansen, 1972). The model results for a fully fixed and shear interface 5 × 5 m square bulkhead provide a close correlation to the calibrated yield line solution proposed by Beer (1986), whereby the basic solution is multiplied by a factor of 1.72. This may explain why the solution proposed by Beer (1986), with the 1.72 safety factor applied, has been used successfully throughout the Australian paste fill industry. However, it is clear that the yield line solution proposed by Beer (1986) is only accurate for flat square bulkheads with simplified boundary conditions, uniform loading and construction materials similar to plain concrete.

The construction of arched bulkheads has been demonstrated to significantly increase the ultimate failure pressure of flat bulkheads.

Realistically, numerical modelling cannot be used alone as a basis for bulkhead design. Back–analysis of measured material properties and field instrumentation is essential to confidently apply numerically derived bulkhead designs to new bulkhead conditions.

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