Simulation of Bedding Planes in Finite Element Analysis of Underground Structures

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ABSTRACT

Bedding planes may allow strata units to separate from or slide over each other, and as such will significantly affect the load transmission between the strata units. The ability to handle bedding planes is considered to be one of the most important facilities of any FE program, as the behaviour of a structure may be governed more by the bedding planes than the individual strata units. This paper attempts to determine the infuence of bedding plane properties on the stability of underground structures by means of a special element, the GAP element, in the 3-D finite element code NASTRAN. The research also endeavoured to determine if the ratio of horizontal to vertical stress had any effect on the action of the bedding planes.

1. INTRODUCTION

Any interface or bedding plane (referred to as bedding planes in this paper) between the coal and surrounding strata, and /or between the strata units around an underground opening usually represents a sudden change in the mechanical and structural properties of the media. The bedding planes have their own material properties, such as axial and transverse stiffness, cohesion and coefficient of friction. These properties usually vary when the bedding plane is structurally active. When a joint is open and /or the normal stress is low to moderate, its stiffness, tensile strength and coefficient of friction are less than those of the adjacent strata. But when the bedding plane is closed and / or the normal stress is high, the mechanical properties of the bedding plane are similar to the surrounding strata.

2. THE BEDDING PLANE MECHANISM

In general, as underground structures are created and the stress state is redistributed, slip and /or separation may occur if the frictional resistance and /or the tensile strength of the bedding plane is overcome. Once the bedding plane starts to slip or open, the build up of horizontal and vertical stress around its location will decrease, thereby reducing the shear stress on the adjacent strata and changing the stress pattern in that region. The strata and the bedding plane itself will respond to these changes; for example the vertical abutment stress will be transferred farther into the rib reducing the normal stress over the bedding plane and in consequence causing the bedding plane to slip more. Also the confining pressure on the pillar will be decreased reducing coal pillar strength (Iannacchione, 1990). These progressive changes may eventually result in serious instability. Babcock and Bickel (1984) suggested that a mechanism such as this can create a coal burst. Factors such as the property of the bedding plane, property of the strata, stress state and geometrical configuration of the structure influence this mechanism.

In the course of this research, two different series of models, Fixed and Gap Models, were constructed and analysed to study the significance of properties of bedding plane on the behaviour of underground structures. The 3-D finite element code, NASTRAN, was used for this purpose.

Fixed Model: In this model adjacent strata units are connected to each other, and no transitional element is considered. This model suggests that the two strata are tied together and act as one. After analysing the model for stress and displacement, the induced stresses on the interface, including shear and normal stresses are obtained.

Using these stresses and the properties of the bedding plane a safety factor against shear (along the bedding plane) can be determined using Euation 1;

$$S.F = \frac{\mu \cdot N}{\tau} \qquad (1)$$

where,

S.F = shear stress safety factor,

N = normal stress on the bedding plane (MPa),

μ = coefficient of friction of the bedding plane, and

τ = shear stress on the bedding plane (MPa).

The above technique was used for the back analysis of a support system in a Colliery in NSW, Australia (Hematian and Porter, 1993). Based on the results obtained, it was clear that the above technique could be used to design an appropriate support system for a given situation which helps to maintain the integrity of the strata.

Gap Model: In this model the adjacent strata units are connected to each other using special transitional elements called GAP elements. These elements must accurately represent the properties of the bedding planes; axial stiffness before and after closure and frictional properties in case of sliding.

3. THE FINITE ELEMENT CODE

The three dimensional finite element program, NASTRAN, is a general purpose 3-D FE code which can be used for static and dynamic displacement and stress analysis of structures, solids and fluid systems (MSC/NASTRAN, 1991). NASTRAN can be employed to perform linear and non-linear analysis. The non-linear solutions consider both geometrical and material non-linearity. It executes the model with specific material properties under increasing load increments. A GAP element is also included which is used to model structural separation and sliding effects. Figures 1 and 2 illustrate the structural characteristics and load-displacement curves of the GAP element (joint element) employed for modelling the bedding planes.

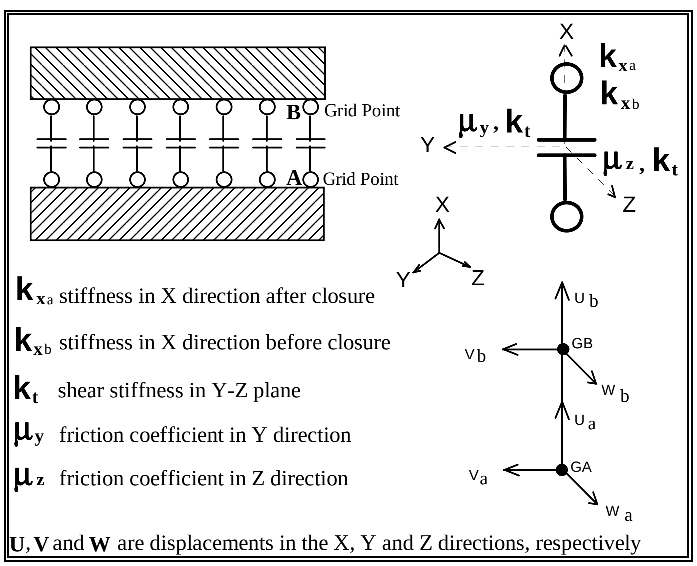

Fig. 1: Structural characteristics of transitional elements called GAP Elements

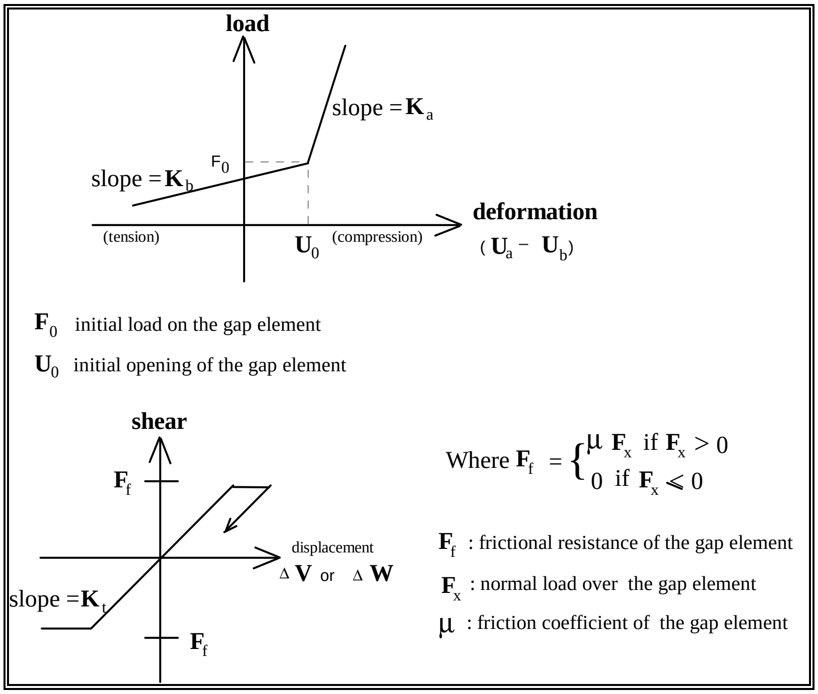

Fig. 2: Load-displacement characteristic of GAP Elements

4. GENERAL DESCRIPTION OF THE MODELS

Two series of models, Fixed and Gap, were analysed under four different load conditions (σ_v = 10 MPa and the ratio of the horizontal to vertical stress, K = 1, 2, 3 and 4) in order to comapre the response of both model types to various stress regions. The horizontal and vertical loads were applied in two different ways. Figure 3 shows the location of the gap-element-modelled bedding plane and the points from where results were obtained. The mechanical properties of the strata units and the bedding plane encountered in these models are summarised in Tables 1a and 1b, respectively. Since a GAP element is considered to have non-linear behaviour, a non-linear method of solution was used to analyse the models. The total load was applied to the model over 5 increments (subcases) to simulate the non-linear load path. Each subcase was performed with 5 iterations to allow the solution to reach convergence.

Table 1a - Mechanical properties of the strata units in Fixed and Gap Models

Property Index (PID) Number	Elastic Modulus E (GPa)	Poisson's Ratio ν
1	20	0.20
2	15	0.22
3	10	0.25
4	3.5	0.30
5	12	0.22
6	15	0.20
7	20	0.22
8	25	0.20

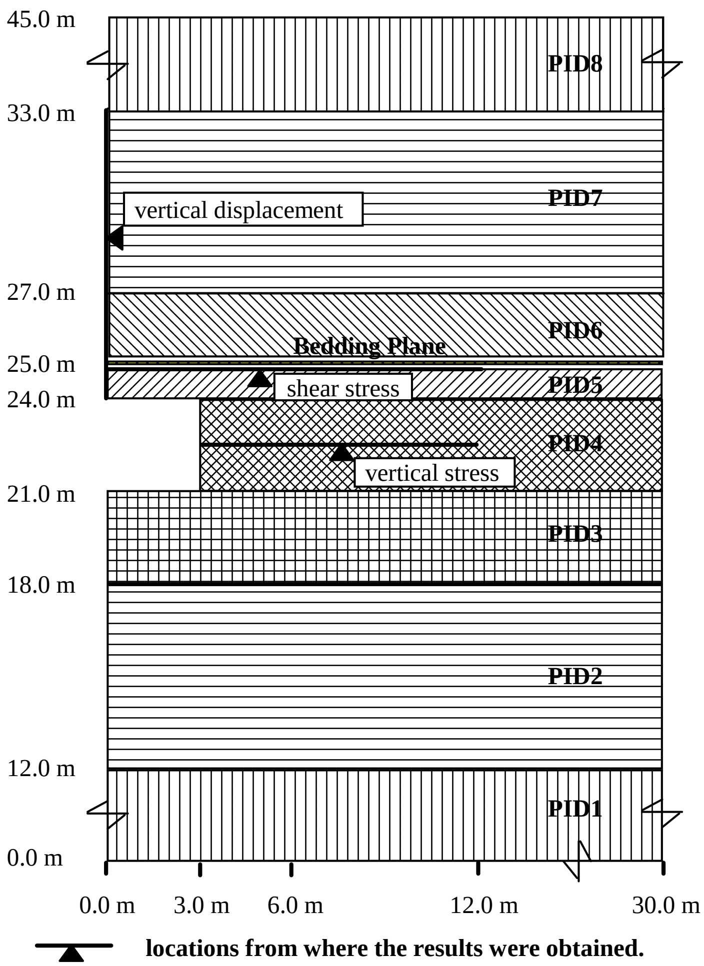

Fig. 3: Location of the gap elements modelling bedding plane and the points from where the results were obtained

Table 1b - Mechanical properties of gap elements used in Gap Models

PID #	u_0	F_0	K_a	K_b	K_t	$\mu y = \mu z$
100	5.0	0	1.1+E12	110	9.0+E8	0.6

where,

u_0 = initial thickness of the gap element (mm),

F_0 = initial load on the gap element (N),

K_a = axial stiffness after closure (Pa / m),

K_b = axial stiffness before closure (Pa / m),

K_t = shear stiffness when gap element is closed, can be $\mu_y \times K_a$, (Pa / m), and

μ_y, μ_z = coefficient of friction in the Y and Z directions.

5. INTERPRETATION OF THE RESULTS

The results from the study are presented in Figs. 4 to 9. These figures illustrate, in a comparative form, the variation of the results obtained from the fixed and gap models under various loading conditions.

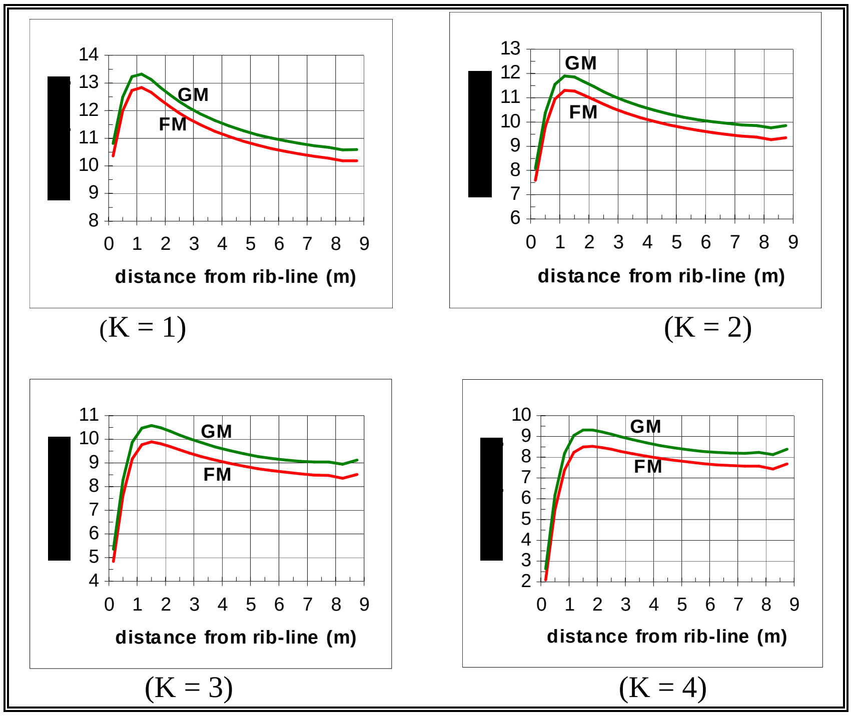

Fig. 4: Vertical stress at the mid-height of the pillar from the Fixed and Gap Models (no separation of the bedding plane)

When loading conditions are such that the bedding plane remains closed the results suggest that the vertical stress at the mid-height of the pillar, indicated in Fig. 4, do not vary significantly between the fixed and gap models; in actual fact showing a fairly constant 1 MPa difference for any given point. This is as expected, as the gap remaining close would allow the rock to act as a fairly cohesive unit. Conversely, when loading conditions are such that the gap opens (Fig. 5), there is a significant variation in the results; particularly at the abutment (note the variation in scale). The fixed model produces the same results (as expected), however, the gap model shows a significant increase in the peak abutment stress and depending on the horizontal stress, reaches a value between 4 and 5 times the situation, as the gap element allows separation across the bedding plane, the lower roof layer acts as a beam held at the abutments. This situation is closer to reality, as literature suggests that the peak abutment load is between 3 and 5 times the cover load (Wilson, 1972) and occurs some distance into the rib (the coal at the edge of rib fails, pushing the stress concentration further into the rib where it can be accommodated due to the triaxial conditions).

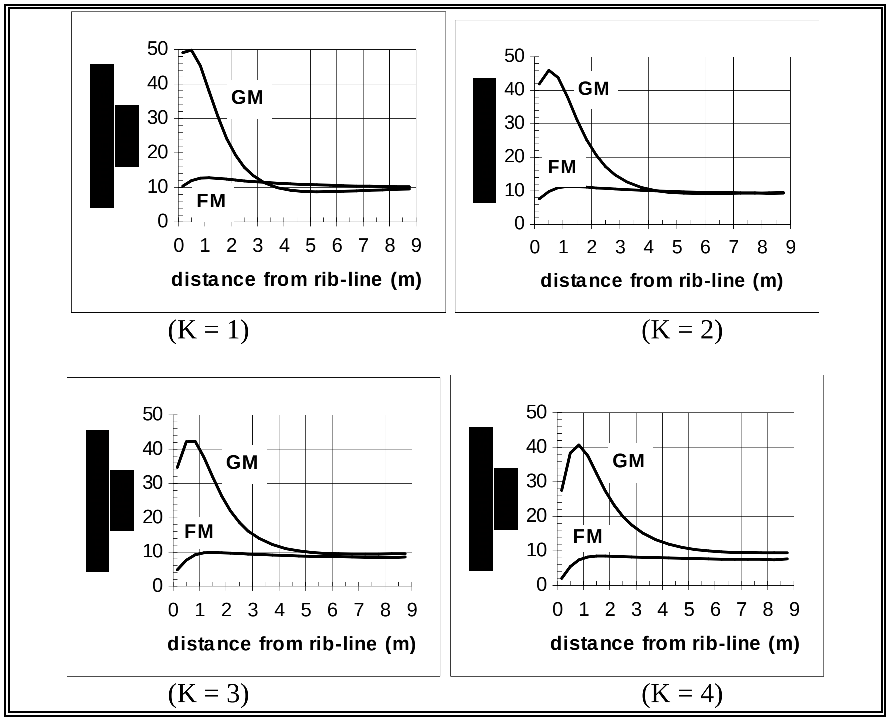

Fig. 5: Vertical stress at the mid-height of the pillar from the Fixed and Gap Models (separation of the bedding plane in the gap model)

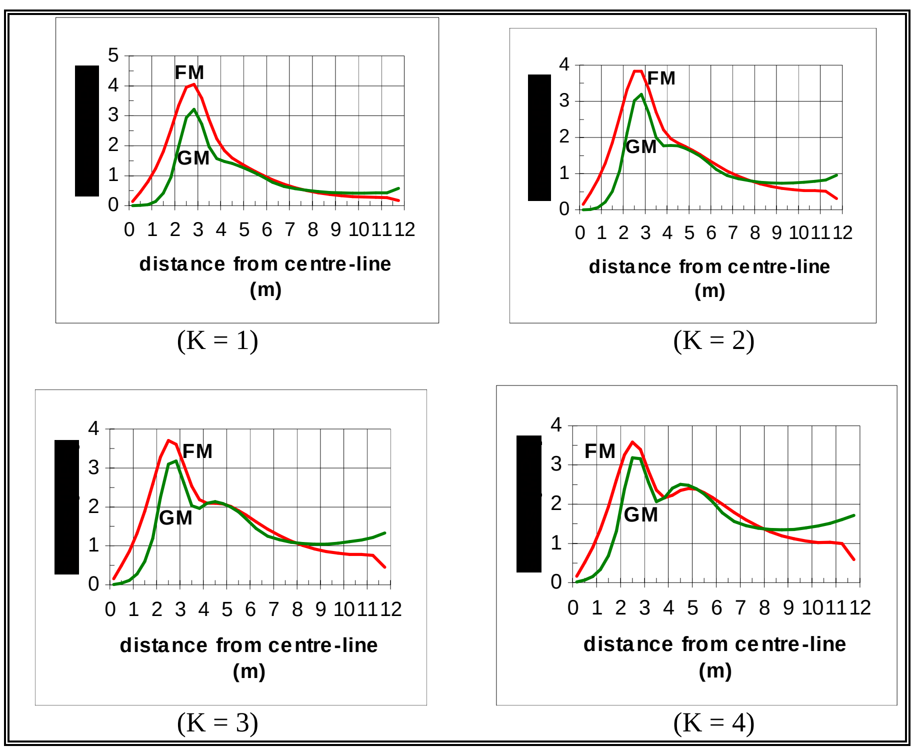

Fig. 6: Shear stress in the elements beneath the bedding plane from the Fixed and Gap Models (no separation of the bedding plane)

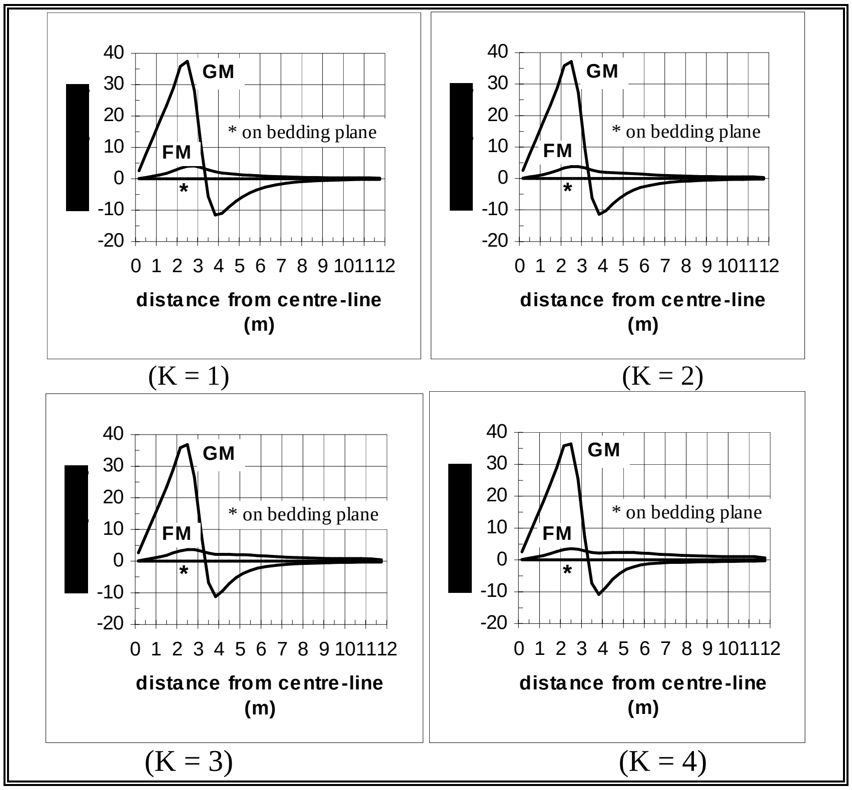

Fig. 7: Shear stress in the elements beneath the bedding plane from the Fixed and Gap Models (separation of the bedding plane in the gap model)

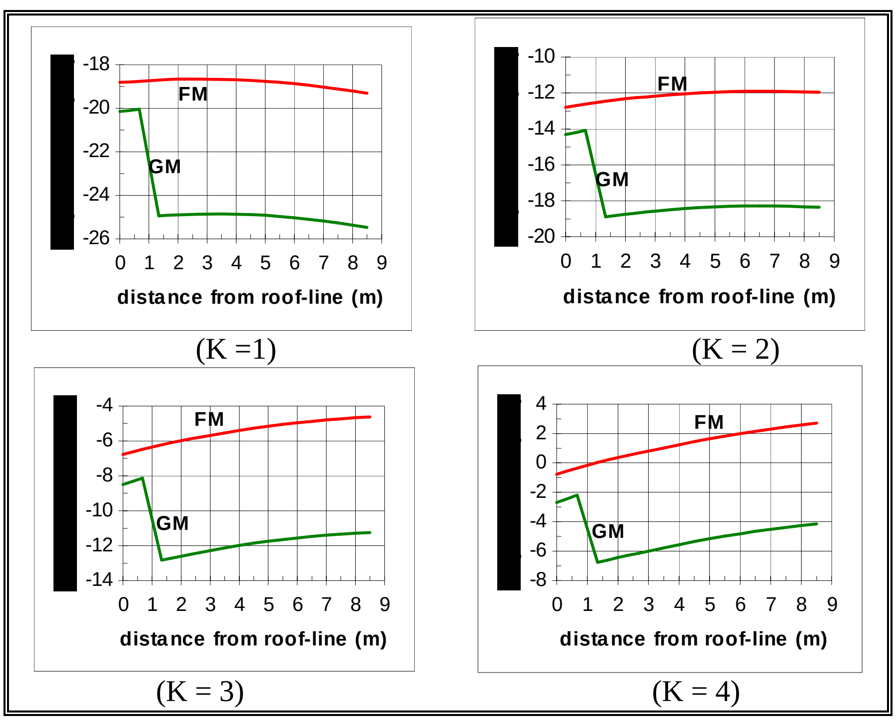

Fig. 8: Vertical displacement along the centre-line from the Fixed and Gap Models (no separation of the bedding plane)

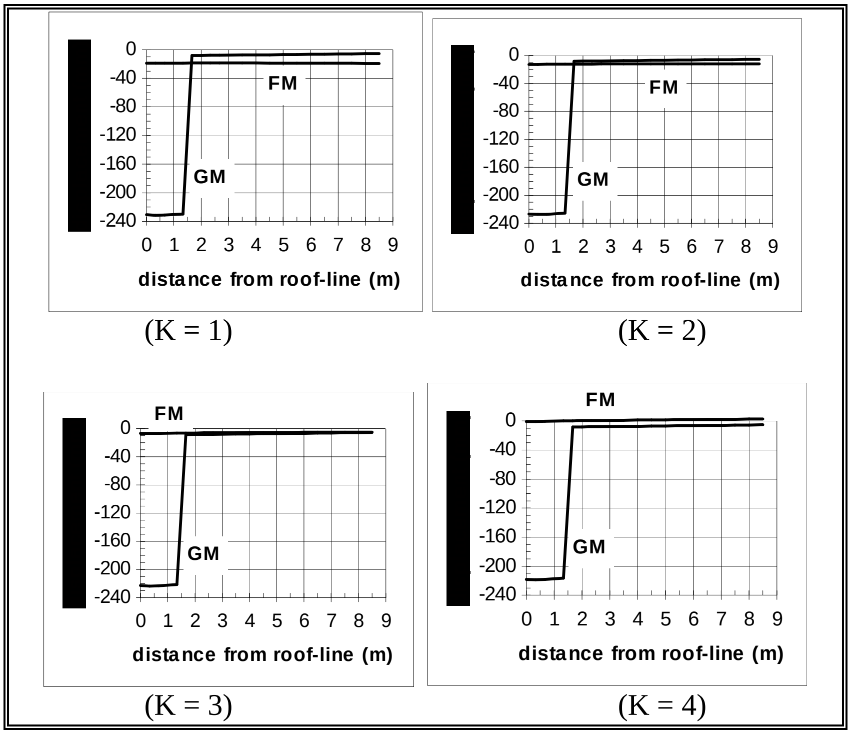

Fig. 9: Vertical displacement along the centre-line from the Fixed and Gap Models (separation of the bedding plane in the gap model)

Similar to the above analysis, Figs. 6 and 7 show the shear stress in the elements directly below the bedding plane for both the fixed and gap models, with and without separation. When no separation occurs, the shear stress in the elements of both the fixed and gap models are similar (Fig. 6), with the peak shear stress occurring at the edge of the ribs. Now comparing the results when the gap element is allowed to open, Fig. 7 shows quite a significant variations. On the bedding plane in the gap model, the shear stress is zero as expected (this was a check that the model was performing to expectations). The fixed model acts as before, but the gap model shows a dramatic increase in the shear stress at the rib edge, dropping to a negative at a distance of 1.5 metres into the ribs. It will also be noted that increase in the horizontal stress field do not affect the results significantly (due to no buckling of rock layers). This increase in shear stress is, as before, caused by the clamped beam of the rock beam deflecting into the opening which causes stress concentrations at the rib edge.

Figure 8 shows that although separation does not occur, there was still some movement of the roof strata towards the opening. Also, the gap model shows closure of the gap. When separation of the gap element occurred (Fig. 9), the lower roof beam deflected significantly, but the roof which essentially acts as a fixed model had displacement similar to that of the initial model. This comparison would be important when determining the effect that roof bolting has on controlling strata movement.

6. CONCLUSIONS

The goal of the investigation was to accurately model bedding planes using the gap element (non-linear joint element), and compare the results from models which used the gap element with models which did not utilise a gap element. Three scenarios were analysed; vertical stress across the rib, shear stress in elements below the bedding plane and vertical displacement of the roof strata. In all cases there was a significant variation in the results obtained from the fixed and gap models. The peak vertical stress in the abutment of the gap model was between 4 and 5 times the virgin stress , comparing favourably with figures reported in literature. Similarly, the shear stress and vertical displacements of the gap model were far closer to reality than the results from the fixed model. Thus, it can be concluded that it is essential to utilise a gap element to accurately model the action of bedding planes in laminated strata.

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