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DESIGN COMBINED SUPPORT UNDER ARBITRARY IMPULSIVE LOADINGG

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ABSTRACT: Rock bolts and cable bolts are usually considered to experience static loads under relatively low-stress conditions. However, in burst-prone conditions, support elements are subjected to dynamic loading. Therefore, it is important to understand cable bolt behaviour under dynamic loading conditions, particularly their energy absorption capacity. Rock bolts and cable bolts as well as steel mesh are widely used as permanent support elements in tunnelling, underground excavations and surface slope stability. This paper aims to determine the amount of the dissipated energy which can be taken into account to design combined yielding supports when subjected to dynamic loading. A ground support approach is suggested for underground excavations undertaking a range of mining-induced coal burst. A bench mark based on the largest expected impact loading is considered to conclude the level of coal burst risk and select an appropriate approach, whether quasi-static or dynamic, for the mine support.

INTRODUCTION

Current coal burst control techniques can be classified into two groups: preventative controls and mitigating controls. Preventative controls to avoid occurrence of coal bursts are usually implemented at the start of underground mines by optimising the mine design, while mitigating controls are applied as risk mitigation measures to minimise the risks of coal bursts during mining. Coal burst risks still exist even when preventative controls are implemented (Wei, *Zhang, Canbulat* et al. 2018). Due to the unpredictability of coal burst occurrences, ground support is usually the final and most common line of protection to ensure safety in high risk zones (Cai, 2013). Ground support has a pivotal role in a dynamic environment, which has been well recognised by the mining industry (Cai 2013; Jiang, et al., 2014; Mikula and Brown, 2018). The dynamic capacity of ground support has been the subject of significant research during the last two decades. However, ground support designs (i.e. yielding support) for coal burst is an area where rock engineering is still developing (Potvin, et al., 2010).

A combination of axial and shear is the primary failure mechanism as the bedded strata formations move in various directions (Mirzaghorbanali, et al., 2017). Aziz, et al., (2015) described that cable bolts are usually installed perpendicular to the sedimentary rock bedding planes above coal mine openings. Rock movement caused by complex ground stresses usually occur along the bedding planes, resulting in shear stress across the cable bolts. Aziz, et al., (2009) conducted a series of double shear tests to investigate the performance of reinforced bolts in shear under different axial loading conditions. A total of 22 rock bolts with different surface profile configurations were tested, and the effects of various tension loads on the load transfer characteristics of the bolts were also studied. The results showed that the level of the shear load was affected by the ultimate tensile strength of rock bolts as well as the axial loads applied during testing. The shear loads increased with increasing tension loads, and the shear load was affected by the bolt profile configuration.

Rock bolts with energy-absorbing capacities play a critical role in the performance of dynamic ground support, and there are a range of products available including D-Bolts, cone bolts,

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Durabar, Roofex, Garford and CRLD (Cai, 2013; Kabwe and Wang 2015; Pytlik, et al., 2016; Wei, *Zhang, Canbulat,* et al., 2018; Zhou and Zhao, 2011). Of these, the cone bolt, Durabar, Garford solid bolt and Roofex are two-point anchored into the rock; the D-Bolt is multi-point anchored; and the hybrid bolt and inflatable bolt interact frictionally with the rock mass along their entire lengths (Zhou and Zhao, 2011). The dynamic capabilities of ground support are key design parameters when selecting yielding elements for highly stressed, burst-prone or high deformation environments (Plouffe, et al., 2007).

STATIC AND DYNAMIC MODELLING UNDER APPLIED SHEAR LOADING

The proposed three-dimensional finite element model is developed using the commercial software ABAQUS, due to its ability to deal with complex contact problems. The structural response of the cable bolts using solid elements for all components is examined using the modelling (Tahmasebinia et al 2018). One of the main difficulties in the modelling of steel and concrete members with ABAQUS is the convergence issues which need to be addressed due to the extensive number of contacts required to be implemented between the cable bolt and the concrete boxes. For this purpose, the 8-node linear brick element (C3D8R) with a reduced integration and hourglass control is adopted, which is the element with three transitional degrees of freedom. To validate the finite element models and the developed analytical solution, the obtained results were compared with the reported experimental investigation by Mirzaghorbanali, et al., (2017). The reported tests were conducted under static loading, which was used to calibrate the models. Then, the models were extended to dynamic loading (Figure 1).

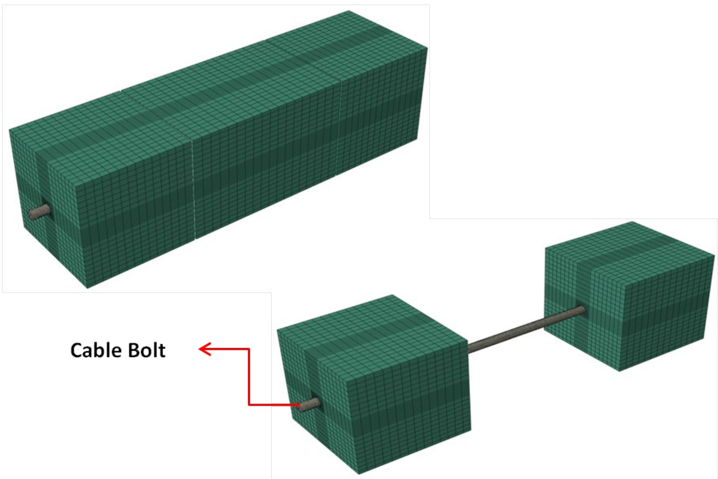

Figure 1: An example of a 3-D finite element model under static and dynamic loading.

One of the significant contributions of this study is the development of an analytical solution to assess the behaviour of the cable bolt under quasi-static loading (Tahmasebinia et al 2018). An equation based on the plastic analysis is proposed. The plastic hinge concept stems from the ability of steel to be idealised as elastic-perfectly plastic. Integrating the fully plastic section is equated to taking the moments of the fully plastic stress block forces about the plastic neutral axis. The principle of virtual work is used to calculate the load magnitude at which the plastic mechanism develops and failure occurs. It means that the external work done by the applied load must equal the internal work done by the plastic hinges in the cable section (Figure 2).

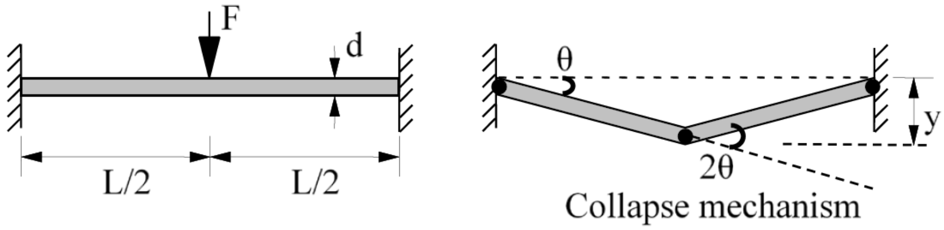

Figure 2: Plastic collapse load of a cable bolt.

The applied shear load versus shear displacement can be calculated by Equation 1

$$F_{\max} = \frac{(k \times N_u \times y_i)^2}{M_u \times L} + \frac{8 \times M_u}{L} \tag{1}$$

where $F_{\max}$ is the transverse shear force; $0.1 \le k \le 0.5$ the constant-coefficient; and y_i displacement increments. Also,

$$N_u = \frac{\pi \times d^2}{4} \times f_y \tag{2}$$

$$M_u = \frac{\pi \times d^3}{2} \times f_y \tag{3}$$

where

N_u is design axial tension capacity;

M_u the design bending capacity,

L the cable bolt length,

d the cable bolt diameter; and

f_y the cable yielding stress.

y_i displacement increments can be obtained by Equation.

$$y_i = \begin{Bmatrix} 0 \\ 0.1 \times d \\ 0.2 \times d \\ \ldots \\ 1 \times d \\ 1.1 \times d \\ 1.2 \times d \end{Bmatrix} \tag{4}$$

Mirzaghorbanali, et al. (2017) conducted a series of double shear tests on different cable bolts by developing a new double shear apparatus without contact between concrete blocks to determine the pure shear strength of pre-tensioned fully grouted cable bolts. Figure 3 and 4 illustrate the failure procedure of the cable bolt which is embedded inside the concrete blocks starting from initial deformation until pure shear failure. This can be one of the advantages of using numerical modelling to assess the local behaviour of cable bolts under static loading in the different stages of the failure. After calibrating the numerical models under static loading, the structural behaviour of the simulated models under dynamic loading was also studied. Since preparing the laboratory experiments to simulate the behaviour of cable bolts under dynamic loading is demanding, a validated and novel numerical simulation was developed. To simulate the behaviour of the cable bolts under impact loading, a 110 kg mass at the velocity of 0.2 m/s was dropped on top of the concrete blocks. Figure 5 presents the structural behaviour of the cable bolts under impact loading. As illustrated, the momentum energy from the dropped mass is initially transferred to the concrete surfaces, and the transmitted energy due to the impulsive loading reaches the cable bolt.

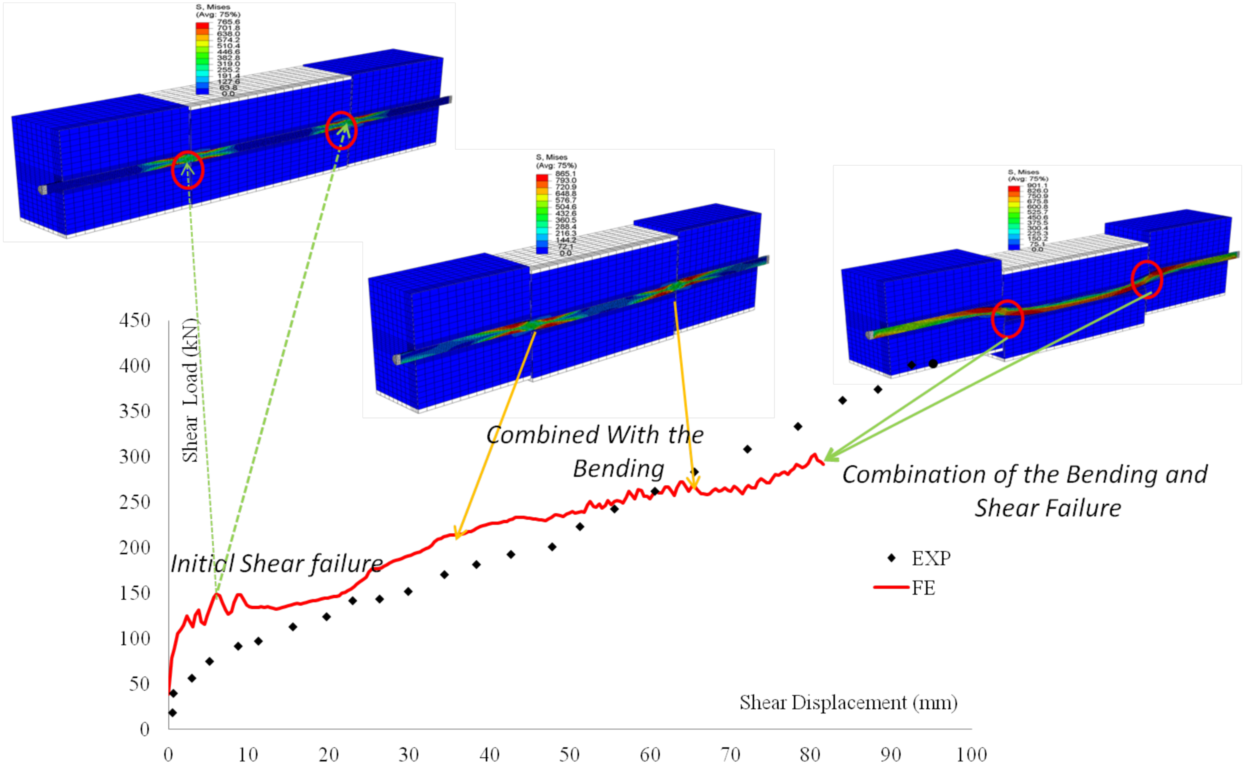

Figure 3: Shear ductile failure in the cable bolt under static loading, shown in different stages.

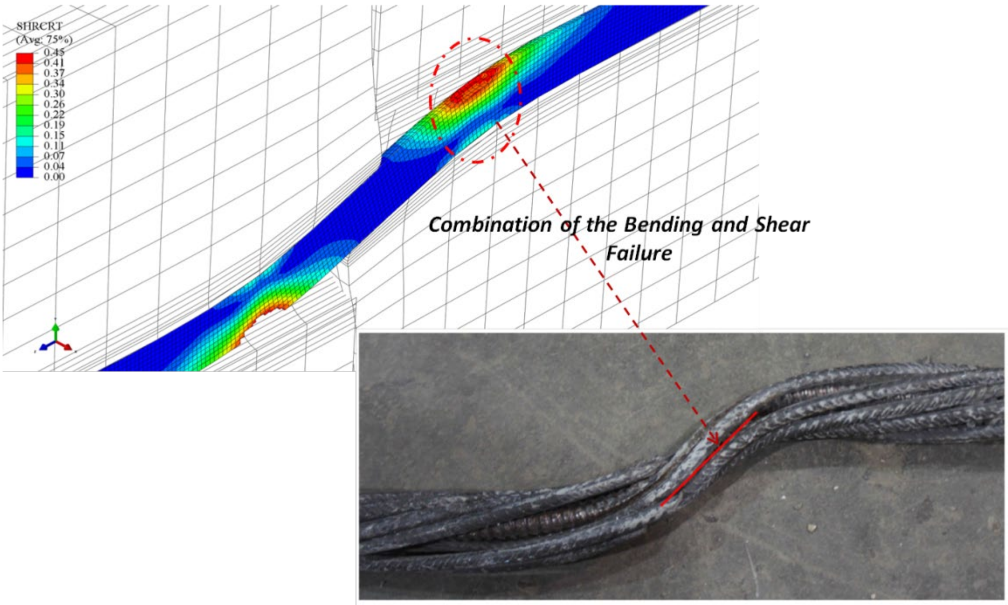

Figure 4: Combination of the bending and shear failure (Mirzaghorbanali, et al., 2017).

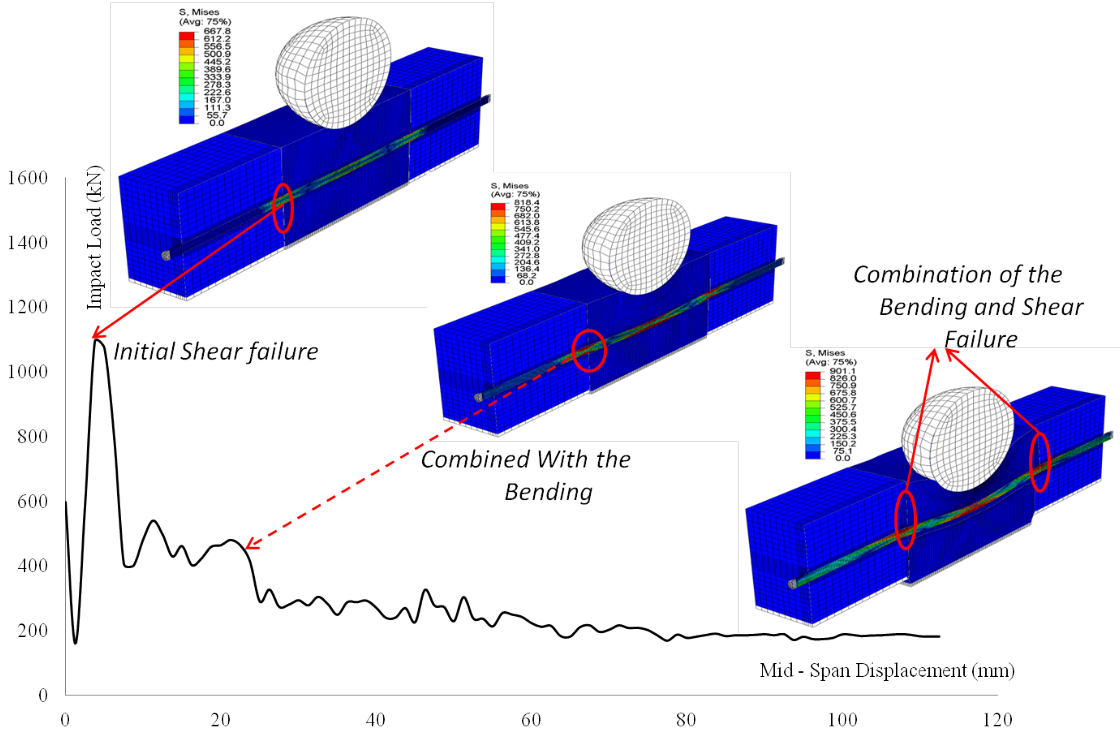

Figure 5: Shear ductile failure in the cable bolt under impact loading, shown in different failure stages.

SIMULATION OF THE BEHAVIOUR OF THE STEEL MESH UNDER DYNAMIC IMPACT LOADING

A similar way to simulate the dynamic behaviour of the steel mesh due to the applied dynamic loading was taken into account. The mesh steel reinforcement sizes 20 mm diameter arranged by 100 mm distance centre to centre of the steel bars were tested under free fall of the dropped hammer. The dropped hammer used in the last section was used for this simulation. The 110 kg drop hammer at velocity of 1.5 m/s was dropped on top of the steel reinforcement. Figure 6 illustrates the experimental set up used to simulate the structural behaviour of the steel mesh under impact loading. Steel mesh can play a significant role as part of the yielding support in a coal mine, as it can mitigate the effect of the destructive released kinetic energy due to a possible coal burst. In coal mines, it was observed that both rock bolts and cable bolts might lose the initial bond stiffness at the early stage of the applied dynamic loading due to the failure and separation of the anchored zone in the cable and rock bolts inside embedded coal. The anchorage length in a post-tensioned member and the magnitude of the transverse forces (both tensile and compressive), that act perpendicular to the longitudinal prestressing force, depend on the magnitude of the prestressing force and on the size and position of the anchorage hooks. Both single and multiple anchorages are commonly used in coal mining. Prestressing force anchors transfer large forces to the coal in concentrated areas. Coal is a very brittle material which can cause localised bearing failure or split open the end of members. Thus, the steel mesh can considerably reduce the effect of the induced dynamic loading due to coal burst. In the current simulation, the tensile stress for the steel mesh was $f_y = 500\ MPa$ and the ultimate stress for the steel mesh $f_u = 700\ MPa$ was taken into account. The post failure of the steel mesh which may rupture the steel bars was also defined. The ductile damage function was determined to simulate the post failure of the steel mesh. Also, the rupturing strain $\varepsilon_{rupture}$ = 0.3% was assumed. As the weld properties of the steel mesh can also influence the overall deformation as well as energy absorption of the yielding support, the weld properties were specifically defined in the present steel mesh simulations. The allocated fracture energy which has a considerable role in determining the separation of the welded steel was specified by computing the area of the obtained stress-strain curves from the weld properties.

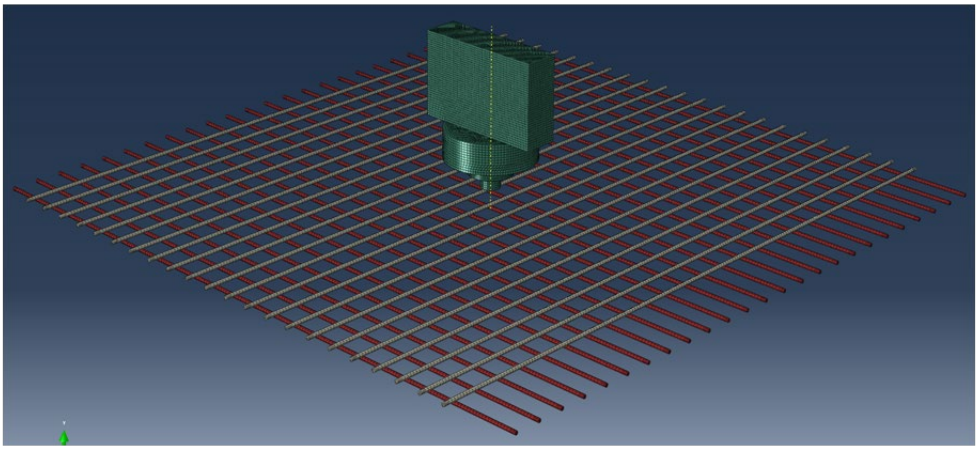

Figure 6: The test set up for simulating the behaviour of the steel mesh under impact loading

Figure 7 demonstrates direct brittle failure in the steel mesh under impact loading in different failure stages. As illustrated, at the initial contact between the dropped hammer and steel mesh, the momentum energy was transferred from the common surfaces. The transferred energy due to the dropped test was distributed in different layers of the steel mesh. The transmitted kinetic energy can induce both shear and bending stresses in the steel mesh. As soon as any steel mesh or welding elements reached the yielding and ultimate stresses, permanent deformation of the steel mesh occurred. This permanent deformation might be followed by the rupturing strain which leads to element separation in the simulated model. In general, connections between the steel bars or location of the weld elements are the weakest position in the steel meshes. Thus, the expected failure can occur around the welded connections. This is one of the main reasons why weld properties can play a significant role in generating the overall ductility, the deformability of the steel mesh, and the amount of the energy absorption in both the yielding and combined supports.

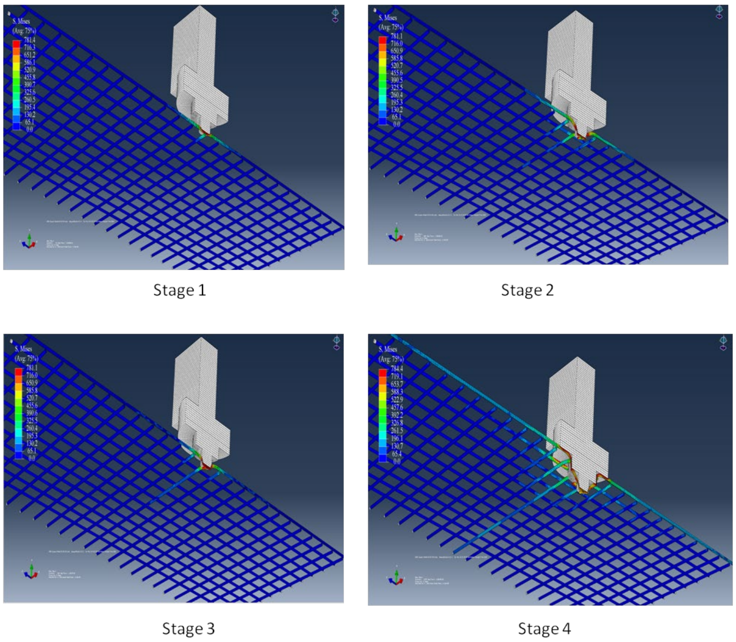

Figure 7: Direct brittle failures in the steel mesh under impact loading, shown in four stages.

Figure 8 shows the interaction between the steel plate and welded wire mesh. This figure indicates that steel plates may be subjected to high levels of stress concentrations. Thus, steel plate buckling capacity in different modes is one of the key factors that may be taken into account when computing overall capacity of a combined support.

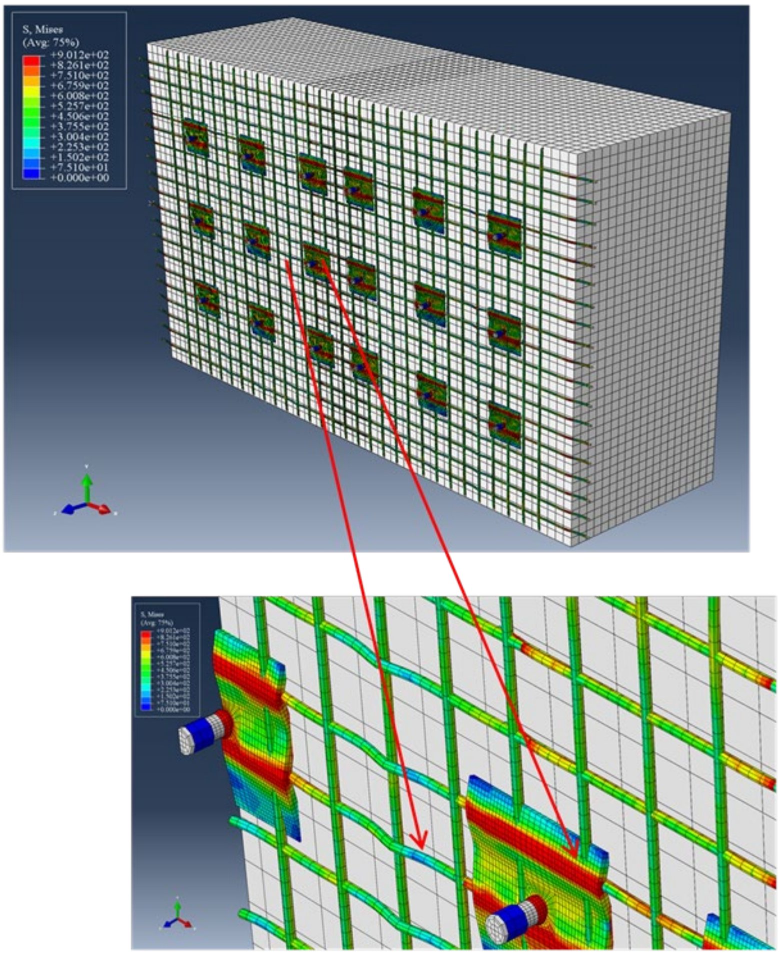

Figure 8: The interaction between the steel plate and weld mesh.

A similar failure pattern can also be observed in a full scale combined support under loading due to rock ejection. The failure process is illustrated in four stages in Figure 9. The tensile stress caused by the ejected rock mass is transferred on to the steel mesh. Also, while some parts of the steel plates are subjected to the tension, the parts are subjected to the compression due to a combination of the bending and shear reactions around the connections of plates. Similar to the conclusions in the previous section, it is also evident that steel plates can play an important role in controlling the deformability of the steel mesh. Details of the failure stages from the initial steel mesh deformation and buckling of the steel plates are demonstrated in Figure 9. This figure also indicates that the deformed shape of the steel plate can enhance the overall deformability of the welded wire mesh when it is subjected to the impact loading.

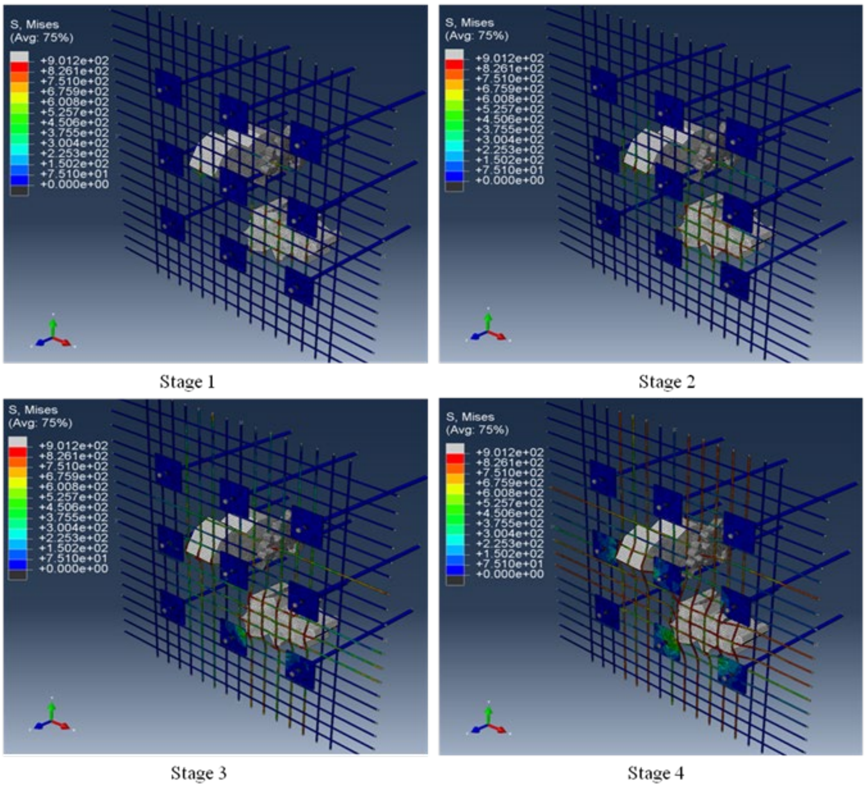

Figure 9: The deformation of the combined support when subjected to the arbitrary fractural rock fall.

CONCLUSIONS

This study tested different key elements in combined support under virtual impact loading to complimentary replace testing under real impact loading conditions which is very time consuming and requires access to special impact facilities. The existing impact testing facilities in Western Australia, Canada, Chile and South Africa are expensive and require significant space for the testing facilities. Individual shock absorber equipment must be installed next to the impact frame facilities to create safe and secure testing conditions in the adjacent buildings due to the possible deconstructive effect of the induced impact loading. Special attention should also be devoted to selecting proper measuring equipment to measure induced impact loading as well as the critical displacement in tested samples. For instance, calibrating the load cell located in the head of the impact hammer is a significant task in preparing the impact facilities. Similar complexity can be found when adapting the load cell to the data acquisition system. Filtering and calibrating the data acquisition system due to the effect of the impulsive loading is very cumbersome and requires particular practical experience. The influence of the inertia forces due to the applied impact loading may lead to misjudgment in evaluating the structural performance of the tested sample in the combined support. Thus, developing novel and well validated numerical models to simulate the effect of impact loading on the different key support elements can play a crucial role in designing a combined support in coal mines which might be affected by coal burst.

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