Chapter

A New Concept to Numerically Evaluate the Performance of Yielding Support under Impulsive Loading

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Abstract

The dynamic capacity of a support system is dependent on the connectivity and compatibility of its reinforcement and surface support elements. Connectivity refers to the capacity of a system to transfer the dynamic load from an element to another, for example, from the reinforcement to the surface support through plates and terminating arrangements (split set rings, nuts, etc.), or from a reinforcement/holding element to others via the surface support. Compatibility is related to the difference in stiffness amongst support elements. Load transfer may not take place appropriately when there are strong stiffness contrasts within a ground support system. Case studies revealed premature failures of stiffer elements prior to utilising the full capacity of more deformable elements within the same system. From a design perspective, it is important to understand that the dynamic-load capacity of a ground support system depends not only on the capacity of its reinforcement elements but also, and perhaps most importantly, on their compatibility with other elements of the system and on the strength of the connections. The failure of one component of the support system usually leads to the failure of the system.

Keywords: fully grouted rock bolts, yielding support, coal burst, shear dynamic loading

1. Introduction

Currently, rock/cable bolts and steel mesh are widely used as temporary and permanent support element in tunnelling, underground excavations, and the surface slope stability. A combination of the rock/cable bolts and steel mesh can provide a robust system, which is known as a combined or yielding support. A combined support can transfer the applied external load from the damaged exterior to the confined interior of a rock mass. The load transferring mechanism between the unstable exterior and interior of a rock mass by means of the combined support system is still of the grey areas in designing the support systems. The understanding the load transferring mechanism between the engaged elements in a rock mass will be more complicated when it comes to designing effective elements against rock/coal burst. Ref. [1] defined ground support as a combination of surface support and reinforcement systems. Ref. [1] also mentioned that the words support and reinforcement are usually used interchangeably. Another concept to recall the support system as a membrane system is determined by [2]. Ref. [2] classified the surface support or containment support as the application of the reaction of the forces at the face of the excavation where it can include the techniques and smart devices to establish both local and global supports. These techniques and devices included fill, timber, steel sets, shotcrete, and the steel mesh. Ref. [3] defined rock reinforcement as an enhancement of the overall rock mass properties within the rock mass, and contain all techniques and devices that perform within the rock mass, including rock bolts, cable bolts, and ground anchors. Dynamic support is defined as ground support systems in which it would be available to resist against sudden energy release and dynamic loading so as to uphold the strength of an underground excavation. A number of researchers including [4–8] focused on studying the shear behaviour of rock bolts when it comes to the high stress and jointed rock mass condition. Ref. [9] classified the procedure for rock mass damage mechanisms by including the sudden volume expansion or bulking of the rock due to fracturing of the rock mass around an excavation. Rock mass bulking is a major cause of damage to support burst-prone condition.

2. Overview of research on yielding support

Ansell [10] carried out further tests on another type of energy-absorbing rock bolt made of soft steel. The aim of the test was to determine the strain rate effects on the yield stress and ultimate strength of the steel bars under dynamic loading conditions. The results demonstrated that the strain rate has a pronounced influence on the yield stress of steel bars. Ansell [10] concluded that the yield stress, the ultimate strength, and the energy absorbing capacity increased with the increasing loading rate, and the soft steel bars had a delayed plastic yielding when subjected to the dynamic loading. The impact was plastic during the retardation of the movable components of the testing machine; it was large at the beginning but dropped dramatically as an exponential curve. Ansell [10] also proposed that a rock bolt used under dynamic loading should have high dynamic-yield capacity so that it can resist high peak forces when experiencing impact loading. There are two methods commonly used to test energy absorption capacity of rock bolts under dynamic loading: free fall of a mass and momentum transfer. Plouffe et al. [11] performed the free fall method in the laboratory, where dynamic loading was simulated by dropping a mass over a certain distance onto the impact plate attached to the lower tube. The load and the displacement at the split were recorded by a load cell under the plate and a differential extensometer, respectively. The performance of bolts under dynamic loading was then analysed in terms of loads, displacements, and energy dissipated. The results showed that the potential and kinetic energies were almost equal to each other, and not all the energy was transferred to the support elements. The dissipated energy results in noise and permanent deformation of the domed plate. An experiment was carried out by [12] to estimate the energy absorption capacity of a new rock bolt, named D bolt, which has a large capacity for load bearing and deformation. Both static pull tests and dynamic drop tests were performed to evaluate the characteristics of the D bolt. For dynamic tests, boreholes were simulated by a split steel tube, which was placed in a jig to align it with a drill. During the test, a mass was dropped from a certain height onto a plate connected to the D bolt, and the impact load and the plate load were then measured during the dropping process. The results indicated that the D bolt's impact peak load capacity was slightly larger than the static tensile strength of the bolt. The D bolt absorbed a large amount of energy along its entire length. The bolt was equally loaded in each deformable section which worked alone to stop rock expansion. Ghadimi et al. [13] developed an analytical model to calculate shear stress in a fully grouted rock bolt in jointed rock mass. The model considered the bolt profile and jump plane under pull test conditions. The results demonstrated that shear stress from the bolt to the rock decreased in an exponential rate. This decrease in shear stress is determined by bolt profiles such as the height, width and spacing of rib, resin thickness, material, and jointed properties. Jiang et al. [14] proposed another analytical model of the grouted rock bolt. The coupling behaviour of the rock bolt and rock mass was discussed from the point of displacement. Based on the analysis, the initial force in rock mass was controlled by its displacement. Another finding was that each bolt has at least one neutral point whose position is influenced by the displacement in the rock mass around the tunnel. The axial force of a rock bolt and the shear stress at the interface between the bolt and rock mass were affected by the length of the rock bolt, the internal radius of the tunnel, and the characteristics of the rock mass. A similar analytical model was also proposed by [15], in which the stress of distribution and variation of fully grouted rock bolts in surrounding rock mass were investigated and analysed. Based on the stress equilibrium in a tiny area of a rock bolt and the shear stress transfer mechanism of the interface between the rock bolt and rock mass, the axial displacement differential equation of the rock bolt was developed. Aziz et al. [16] researched the load transfer capacity of fully grouted rock bolts under an elastoplastic rock mass condition and proposed an analytical solution to determine the axial load along the rock bolts. In this model, the rock bolts were assumed to be elastic material and the surrounding rock mass was considered as an elastoplastic material. According to the model analysis, the load transfer capacity of a fully grouted rock bolt can be expressed as a function of various parameters of the surface condition, including bolt length, shear stiffness of the interfaces, in situ stress, and rock displacement along the bolt. Rock bolts are part of the reinforcement support system in underground excavations. It is important to evaluate and understand the performance of bolts under varying loads. Laboratory testing methods, especially the double shear test, can be used to determine the mechanical properties of rock bolts under static loading. Tests for rock bolts under dynamic loading are used to determine the energy absorption capacity, which is an important parameter for describing the dynamic performance of a rock bolt. Numerical modelling by using simulation software and theoretical analysis can also be used to analyse the behaviour of rock bolts in a jointed rock mass. Since experimental investigation of cable bolts under dynamic loading is very complicated and requires sophisticated facilities, numerical modelling can be used as a reliable method.

3. Numerical procedure

The proposed three-dimensional Finite Element model is developed using the commercial software ABAQUS, due to its ability to deal with complex contact problems. In fact, one of the main difficulties in the modelling of steel and concrete members with ABAQUS is in 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. The proposed numerical model is developed to predict the structural response of the cable bolts using solid elements for all components. 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 (**Figure 1**).

One of the main difficulties in the modelling of steel and concrete members with ABAQUS is in 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 blocks. The proposed numerical model is developed to simulate the structural response of the cable bolts using solid elements for all components. 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. The base model in this chapter is similar to the author's previous work [17], where preliminary numerical modelling and analytical study were conducted to examine cable behaviour. This study provides further parametric analysis on bolts behaviour under different conditions. The adequacy and stability of a Finite Element model to describe the behaviour of a cable bolt is strongly influenced by the definition of adequate contact properties between the concrete and steel components, as suggested by [17]. The presence of a large number of contact regions, especially when dealing with cable bolt models, significantly increases the complexity of the analysis due to the nonlinear and discontinuous nature of cable bolts. For this reason, the Finite Element simulations carried out as part of this study are implemented with ABAQUS/Explicit, to avoid convergence difficulties. The interface behaviour between the concrete box and the cable bolt is modelled using the surface-to-surface interaction available in ABAQUS. In particular, a HARD contact property is adopted in the direction normal to the interface plane. For the tangential behaviour, the PENALTY option is used with a friction coefficient of 0.5 between the cable bolts and the grout. The behaviour of the cable bolts is described using a linear elastic relationship up to yielding, followed by a strain-hardening behaviour. The concrete in compression is described with an initial linear elastic range up to 40% of its compressive strength after which it is represented by the Concrete Damage Plasticity model available in ABAQUS. Its

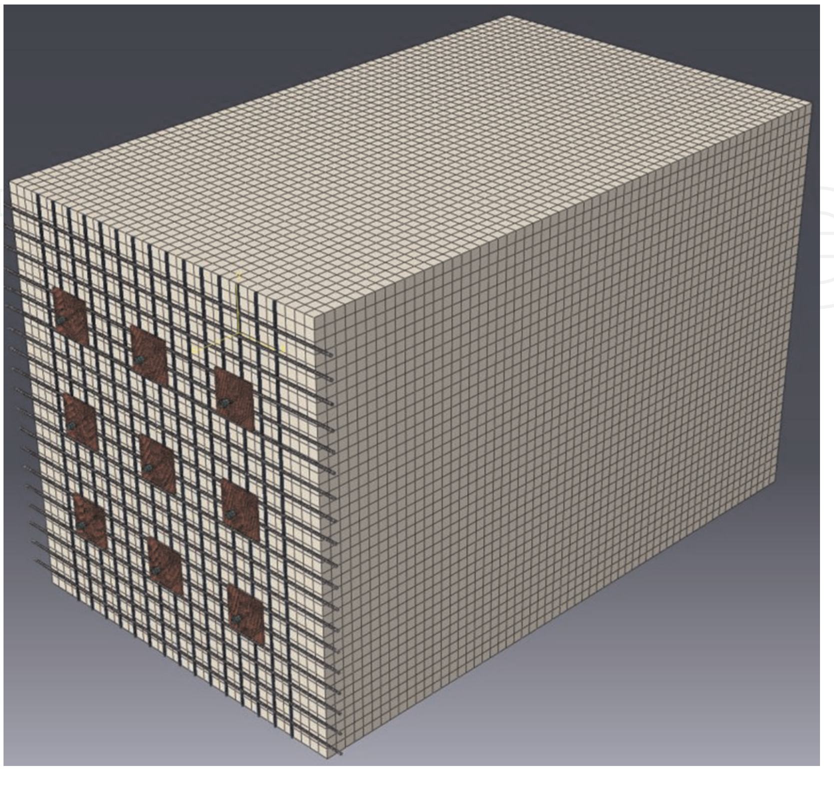

Figure 1.
An example of 3-D finite element models under static and dynamic loading.

tensile behaviour is initially linear elastic followed by a softening response after cracking is initiated.

4. Analytical and numerical solution

Plate is one of the important elements which may influence the overall performance of the combined support. To date, a little attention was devoted by the industry to evaluate the performance of the plate in the roof and rib blot system. The strength of the head plate can be part of a roof or rib bolt system component. However roof bolting system that uses pre-tension for reinforcing purposes may not always achieve full encapsulation, the head plate is in fact a vital component of the system. Thus, at this stage, different and critical buckling modes in a steel plate with hole in the centre of the plate were presented. A number of researchers [18–22] theoretically and experimentally reported buckling of square plates with central circular holes subjected to compression in the plane. The presented theoretical methods by most of the researchers [18–21] calculate the critical loads in a plate with hole in the centre were extracted from the minimum energy method [23]. However, the available methods buckling and post-buckling solutions, which are mathematically discussed, are limited to small hole sizes, and are not able to study the effects of different boundary conditions of the plate on the strengths of buckling plates with holes of arbitrary size. By inventing powerful computers and advantaging from simulating Finite Element software, it is now possible to calculate the stresses of post-buckling for rectangular plates with any aspect ratio, any shapes and sizes of cuts, and in different boundary conditions. **Figure 2** illustrates the applied boundary conditions and the applied pressure on the top and bottom edges. Initially, a fundamental method is presented for computing the compressive buckling load of a simply supported elastic rectangular plate having a central circular hole.

Subsequently, a three-dimensional Finite Element model is developed to comprehensively compute the critical buckling load in a rectangular plate having a central circular hole. The developed models will be extended to simulate the post-buckling analysis in the future research reports. An energy method to determine the buckling load of r rectangular plates of constant thickness under compressive loads is developed by Timoshenko [17]. A review of this derivation shows that the method is also applicable to plates of variable thickness. In this case, Timoshenko's integrals I_1, I_2 are [17]:

$$I_1 = \iint_{Surface} D\left\{\left(\frac{\partial^2\omega}{\partial x^2}+\frac{\partial^2\omega}{\partial y^2}\right)^2 - 2\times(1-\mu)\times\left[\frac{\partial^2\omega}{\partial x^2}\times\frac{\partial^2\omega}{\partial y^2}-\left(\frac{\partial^2\omega}{\partial x\partial y}\right)^2\right]\right\}dxdy \quad (1)$$

$$I_2 = \iint_{Surface} h\left[\frac{\sigma_x}{S}\times\left(\frac{\partial\omega}{\partial x}\right)^2+\frac{\sigma_y}{S}\times\left(\frac{\partial\omega}{\partial y}\right)^2+2\times\frac{\tau_{xy}}{S}\times\frac{\partial\omega}{\partial x}\times\frac{\partial\omega}{\partial y}\right]dxdy \quad (2)$$

where.

h : is the plate thickness (function of x and y), x, y : is the rectangular coordinates with origin at centre of plate and x-axis in direction of load, and ω : is the lateral deflection of plate.

$$D = \frac{E\times h^3}{12\times(1-\mu^2)} \quad (3)$$

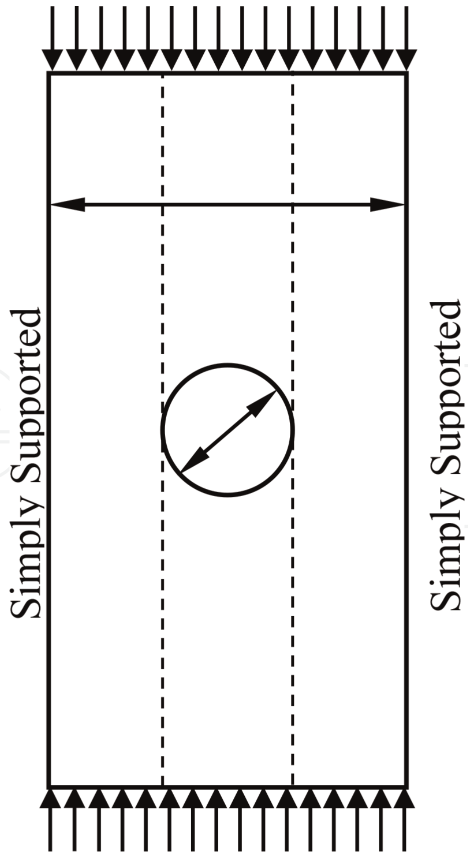

Figure 2.
A simply supported plate subjected to compression.

where D : is the flexural rigidity of plate (function of x and y); $\mu = 0.3$: is the Poisson's ratio; σ_x : is the tensile stress in x direction; σ_y : is the tensile stress in y direction; τ_{xy} : is the shear stress; and S : is the tensile stress in x direction far from hole.

This study investigates the effect of holes on the critical buckling of the web plates of studs subjected to pure compressive load along the length of the plate. The web of the studs is considered to be simply supported along the edges that intersect with the flanges. The buckling analysis is performed using the commercially available finite element software ABAQUS/Standard. In the current research, the general purpose of three-dimensional, stress/displacement, reduced integration with hourglass control, shell element S4R (available in the ABAQUS/Standard element library), is considered to model the plates. S4R is involved in four nodes (quadrilateral), with all six active degrees of freedom per node. S4R allows transverse shear deformation, and the transverse shear becomes very small as the shell thickness decreases.

4.1 Simulation of the behaviour of the steel mesh under dynamic impact loading

A same trend to simulated dynamic behaviour of the steel mesh due the applied dynamic loading was taken into account. Thus, the mesh steel reinforcement sizes 20 mm diameter which they arranged by 100 mm distance centre to centre of the steel bars were tested under free fall of the dropped hammer. The same dropped hammer, which was used in the last section, was considered for the current simulation. It is indicated that a 110 kg hammer was dropped at a velocity of 0.2 m/s on top of the steel reinforcement.

Figures 3 and **4** illustrates the simulated experimental set up which was used to simulate the structural behaviour of the steel mesh under impact loading. It should be noted that steel mesh can play a significant role as a 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 the coal mines, it was observed that both rock bolt and cable bolt might be losing the initial bond stiffness at the early stages of the applied dynamic loading due to the failure and separation of the anchored zone in the cable and rock bolt 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

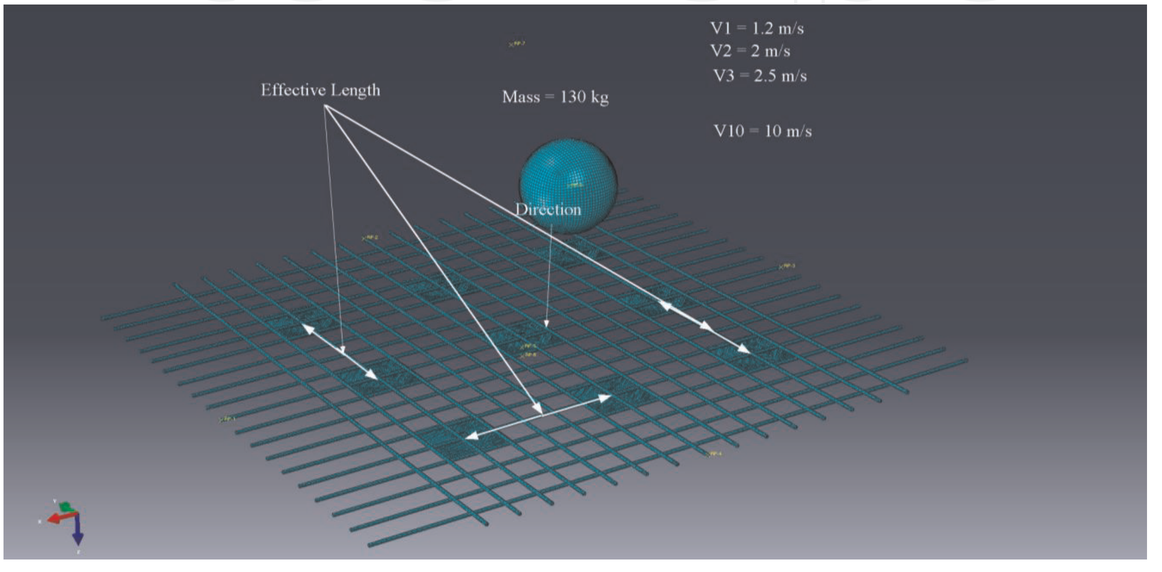

Figure 3.
The testing set up for simulating the behaviour of the steel mesh under impact loading.

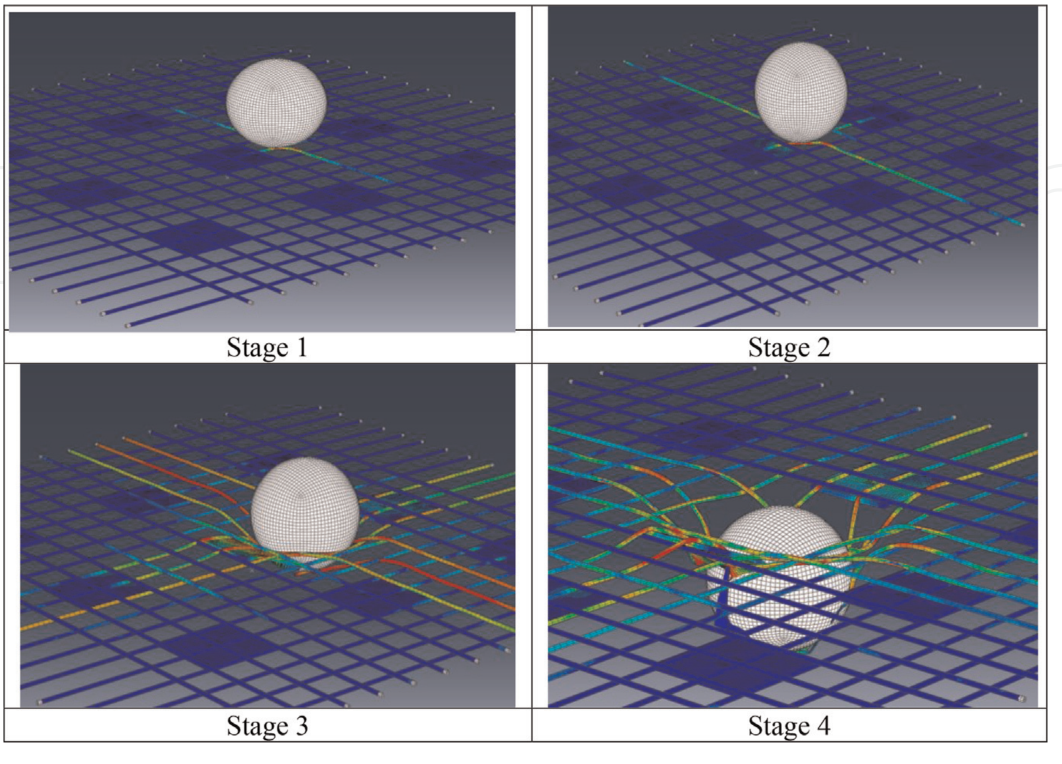

Figure 4.
Simulation of the behaviour of the steel mesh under dynamic impact loading.

anchorage hooks. Both single and multiple anchorages are commonly used in the coal mining. Prestressing force anchors transfer large forces to the coal in concentrated areas. Furthermore, coal is a very brittle material. This 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 the 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 result in the rupturing of 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. Weld properties of the steel mesh can also influence the overall deformation and energy absorption of the yielding support.

4.2 Simulation under dynamic shear loading

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. In order to simulate the behaviour of the cable bolts under impact loading, a 110 kg mass at 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 would initially be transferred to the concrete surfaces. The transmitted energy due to the impulsive loading will reach the cable bolt. **Figure 5** demonstrates the failure process of the cable bolt under the impact loading starting with the initial deformed shape followed by the brittle shear failure. The computation time was

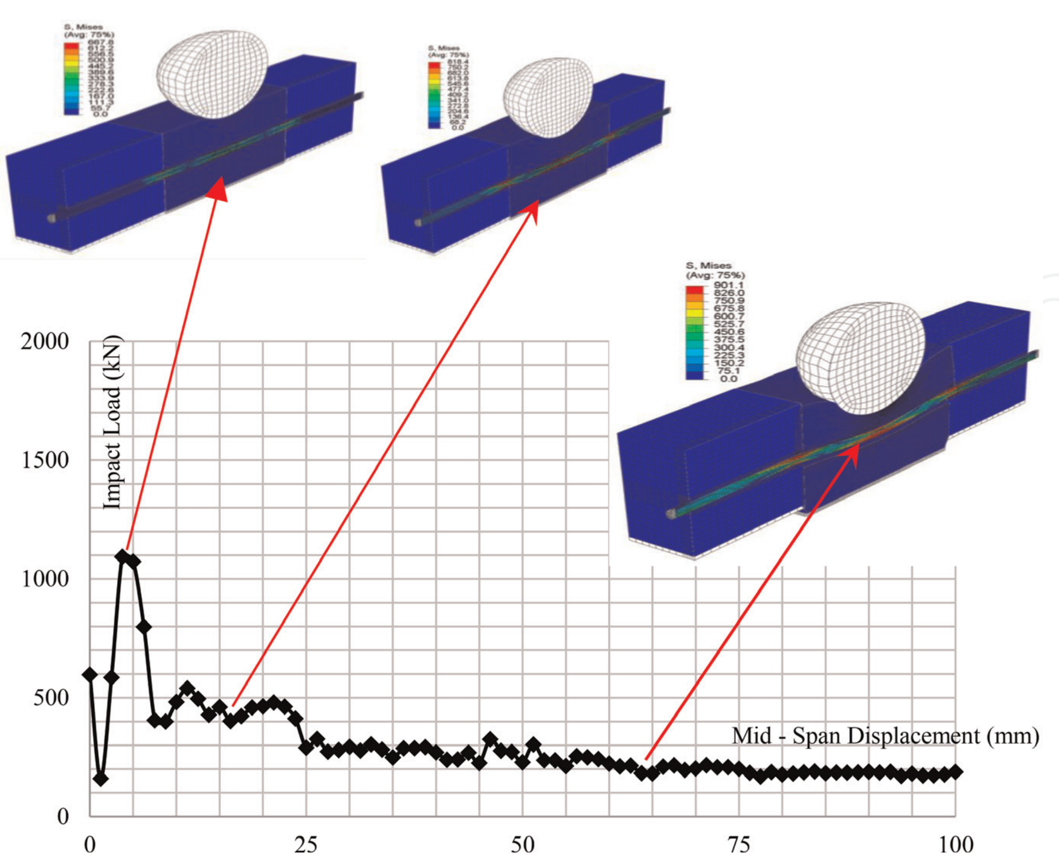

Figure 5.
Cable bolt under impact loading.

around t = 5e-3 seconds, which is very short to simulate the effect of the impulsive loading.

5. Conclusion

A Finite Element model to predict the structural behaviour of cable bolts under both static and dynamic loading was presented. The models were initially calibrated against the experiments available in the literature. By taking the advantage of numerical modelling, some of the localised structural performance of cable bolts under both static and dynamic loading can be observed. By computing the area under curves of the load–displacement curves under both static and dynamic loading, the amount of the absorbed energy in each cable bolt can be estimated. The results indicate that numerical modelling can be used to assess the rock bolt behaviour under dynamic loading for designing the ground support in burst-prone conditions. Numerical techniques can predict an acceptable estimation of the reaction of cable bolts under impact or impulse loading. The most recognised advantages of numerical modelling are that following the initial calibration stage, variety of loading conditions can be modelled and the behaviour of bolts can be studied in greater detail compared with laboratory tests. The current simulations can be taken into account as a cost-effective replacement instead of using drop test facilities. As indicated, drop test facilities are very complicated and expensive. Also, it needs to hire highly skilful technical staffs to calibrate the measurement tools including data acquisition system and the load cell. Subsequently, extracting the induced data after performing the impact test, individually, when it comes to remove the effect of the inertia forces, is one of the significant tasks. In the second section of the current paper, extensive parametrical studies from the developed Finite Element models will be undertaken. The main purpose of doing the following parametrical studies is to determine realistic and technical design guidelines for the combined support against impulsive dynamic loading.

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