Ground Support 2026 - D Cumming-Potvin & J Wesseloo (eds.)
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doi:10.36487/ACG_repo/2625_07

3D finite element modelling of reinforcement systems under dynamic loading using a momentum-transfer approach

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Abstract

Ground support systems in underground excavations must be designed to resist dynamic loading generated by rockbursts and seismic disturbances. There has been growing interest in understanding the behaviour of individual support system components, particularly reinforcement elements, under dynamic loading conditions. Laboratory-based tests play a critical role in evaluating their capacity. In these tests, 2 commonly used approaches, impact and momentum transfer, simulate dynamic loading conditions. The main difference between the 2 methods lies in how energy is applied to the specimen. This study presents a numerical investigation of the dynamic response of reinforcement systems using the momentum-transfer testing configuration. A three-dimensional finite element model (FEM) was developed in ABAQUS to simulate the loading conditions representative of the laboratory test. The load–displacement responses obtained from experimental tests were compared with FEM to evaluate the accuracy of the numerical representation of the support system under loading. The results show that the FEM prediction closely follows the overall trend of the experimental behaviour, capturing both the peak load and displacement response. The maximum load obtained from the FEM is approximately 350 kN, consistent with the peak load observed in the experimental data. The experimentally measured dissipated energy ranged between 8.2 and 9.5 kJ, while the numerical model calculated a dissipated energy of 11.3 kJ. Overall, the results show that the proposed numerical model can reasonably reproduce the main mechanical behaviour of reinforcement systems under dynamic loading. This confirms that the momentum-transfer approach can be used for numerical calibration and for evaluating the performance of support elements. The results also indicate that the momentum-transfer approach can be extended to more complex integrated ground support systems, contributing to a better understanding and improved design under rockburst and seismic loading conditions.

Keywords: *ground support elements, finite element model, dynamic loading, momentum-transfer testing, energy dissipation*

1 Introduction

Rockburst is a complex and hazardous phenomenon commonly encountered in deep underground excavations, particularly in hard rock environments, where elevated in situ stresses can lead to sudden and violent rock failure (He et al. 2025). As mining operations progress to greater depths, the likelihood of rockburst increases due to higher stress concentrations and excavation-induced stress redistribution, posing significant challenges to ground stability, infrastructure integrity, and worker safety (He et al. 2012; Manouchehrian & Cai 2017; Simser 2019; Shakeri et al. 2026). Currently, more than 110 deep metal mines worldwide operate at depths exceeding 1,000 m, with many located in Australia, South Africa, Canada, the United States, India, and Russia, and several extending beyond 2,000 m (Ranjith et al. 2017; Wang et al. 2023;

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An & Mu 2025). These increasing mining depths have intensified the need for robust ground support systems capable of withstanding the dynamic loading associated with rockburst events.

Reinforcement and support elements such as rockbolts, welded wire mesh, and fibre-reinforced shotcrete play a critical role in controlling deformation, containing fractured rock, and absorbing energy generated during rockburst events. These systems are essential for maintaining the stability of excavations under dynamic loading conditions. Experimental test facilities enable controlled assessment of these reinforcement and surface support elements under impact or momentum-transfer loading, providing valuable insight into load transfer mechanisms, deformation behaviour, failure modes, and energy absorption capacity.

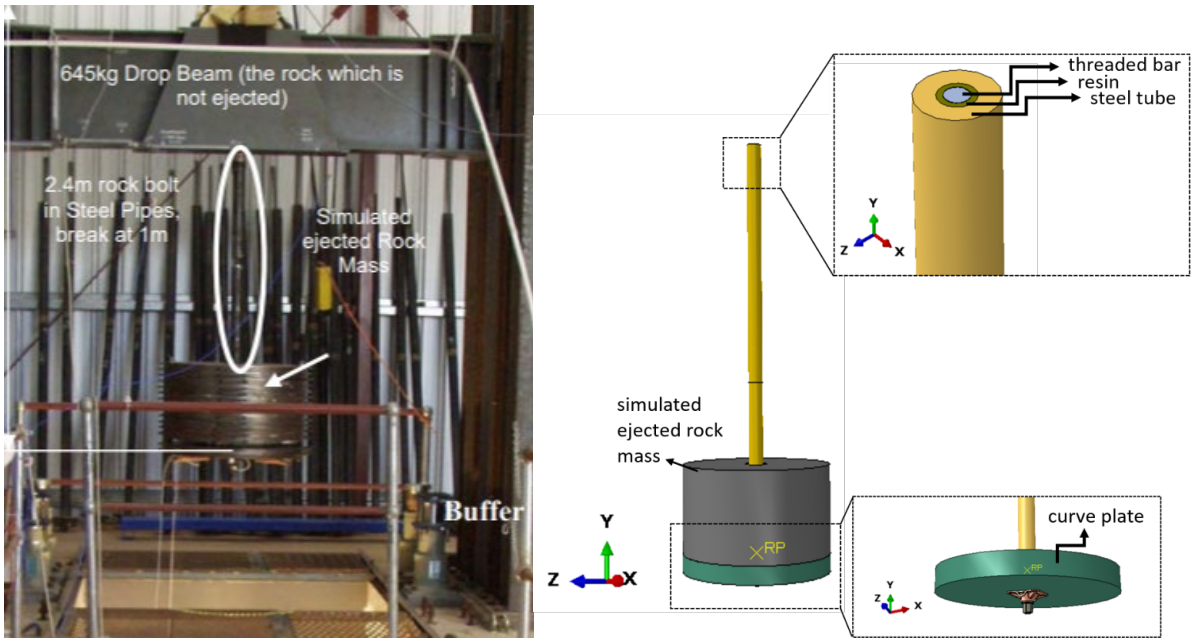
Experimental test facilities can be classified according to the type of support components they evaluate, including individual reinforcement elements, surface support elements, and integrated support systems. Facilities designed to assess individual support elements include the Western Australian School of Mines (WASM), Australia; the National Technical Centre and the Council for Scientific and Industrial Research (CSIR Miningtek), South Africa; the TerraTek Laboratory and Drilling Research Laboratory (Terratek), USA; and the Mining Innovation, Rehabilitation and Applied Research Corporation (MIRARCO), Canada. In contrast, facilities such as the Safety in Mines Research Advisory Committee (SIMRAC) stope test facilities in South Africa and the Geobrugg testing facilities in Switzerland are designed to evaluate the performance of complete support systems. These experimental methods are generally simple, cost-effective, and relatively easy to implement. However, they are often constrained by simplified boundary conditions, limited specimen dimensions, and an inability to fully capture the complex interactions between reinforcement and surface support elements under dynamic loading.

Facilities that test integrated support systems provide a more realistic assessment of support performance under dynamic loading. For example, the Geobrugg testing facility allows full-scale dynamic testing with high impact energy, providing a better understanding of the behaviour of the complete support system. However, these facilities are often expensive to operate, not widely accessible, and cannot fully replicate the in situ stress conditions of underground excavations.

Despite the wide range of experimental facilities available, no single test facility can fully replicate the complex behaviour of ground support systems under rockburst conditions (Hadjigeorgiou & Potvin 2007). Most facilities focus on individual support components or simplify the interactions between support elements. Therefore, combining experimental testing with numerical modelling is essential to improve the understanding of ground support system behaviour under dynamic loading. This integrated approach forms the basis of the present study.

2 Numerical approach for modelling the momentum–transfer method

To ensure the reliability of the numerical model, a calibration study was conducted using the explicit dynamic solver in ABAQUS/Explicit. The study replicated the dynamic testing configuration of the WASM momentum–transfer facility. Figure 1 shows the experimental setup and the corresponding numerical model used to verify the behaviour of the reinforcement system under momentum–transfer loading.



(a) (b)

Figure 1 (a) Western Australian School of Mines momentum–transfer testing facility used for dynamic testing of reinforcement systems (Villaescusa et al. 2015); (b) Corresponding simplified numerical model developed in ABAQUS/Explicit

Figure 1a shows the WASM dynamic testing facility. In this setup, a drop beam simulating an ejected rock mass is released along guided rails and impacts the loading system. The reinforcement element is installed inside steel pipes that represent the surrounding rock mass. The system is instrumented to record the dynamic response. The energy from the falling mass is transferred through a buffer system, which enables controlled deceleration and momentum transfer to the reinforcement element.

Figure 1b illustrates the simplified numerical model developed in ABAQUS/Explicit, designed to replicate the key features of the experimental setup. The reinforcement system consists of a threaded bar embedded in resin and confined within a steel tube. The curve plate and simulated ejected rock mass were modelled as discrete rigid bodies, as their deformation is negligible compared to the reinforcement components and does not significantly influence the overall system response. The remaining components were modelled as deformable bodies to capture their mechanical response under dynamic loading. The loading is applied through a reference point, which represents the motion of the simulated ejected rock mass in the momentum-transfer method. A rigid body is assigned to the impactor with its actual mass, and an initial velocity is prescribed to generate the impact condition. The material properties assigned to the model components are presented in Table 1. Elastic material properties were assigned to the plate, resin and steel tube, as the primary focus of the analysis is on the behaviour of the threaded bar (Zhao et al. 2021).

The curved plate and lower steel tube were restrained in the lateral directions to prevent rigid body motion while allowing axial deformation. The threaded bar was fully fixed at the anchored end to represent the in situ anchorage condition. Table 2 summarises the contact interactions used between the different components of the numerical model. The damper resistance is represented by the contact between the impactor and the support system, together with friction at the contact interfaces. No artificial damping was used. These contact interactions control the transfer of forces between components and are important for simulating the behaviour of the reinforcement system.

Table 1 Material properties of the model components

Support component name	Constitutive model	Density (ρ) (kg/m^3)	Young's modulus (E) (GPa)	Poisson's ratio (ν)	Yield strength (MPa)	Ultimate tensile strength (MPa)
Plate	Elastic model	7,800	200	0.28	–	–
Nut	Elastic model	7,800	200	0.25	–	–
Steel tube	Elastic model	7,800	200	0.25	–	–
Resin	Elastic model	2,000	25	0.32	–	–
Threaded bar	Plastic model	7,800	200	0.28	565	685

Table 2 Interactions and constraints between model components for reinforcement system

Interactions	
Threaded bar-resin	Bond–friction model
Resin-steel tube	Bond–friction model
Bolt plate–curve plate	Binding constraint
Steel tube–curve plate	Binding constraint
Threaded bar–nut	Binding constraint
Plate–nut	Binding constraint

A bond–friction model with a friction coefficient of 0.3 is assigned to the interfaces between the threaded bar and resin (Zhao et al. 2021) and between the resin and steel tube. This interaction allows bonding with slip, representing realistic load transfer between the bolt and grout. In contrast, binding constraints are applied to connections such as bolt plate–curve plate, steel tube–curve plate, threaded bar–nut and plate–nut. These constraints assume a fully rigid connection with no relative motion between the components. This simplification is appropriate for mechanically connected parts where slip or separation is negligible under the applied loading conditions. Figure 2 shows the boundary conditions of the reinforcement system.

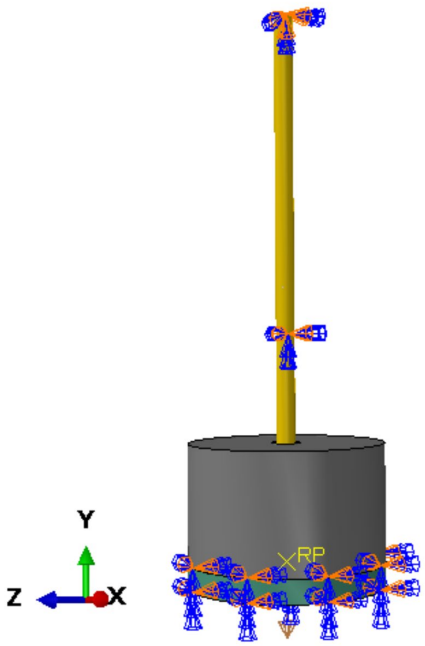


Figure 2 Boundary conditions of the reinforcement system

3 Results

The numerical results provide important insights into the deformation and failure behaviour of the reinforcement system under momentum–transfer loading. A maximum separation of 77 mm is observed at the simulated discontinuity (Figure 3). The equivalent plastic strain (PEEQ), which is dimensionless distribution, shows clear localisation of plastic deformation in the threaded bar, with the highest plastic strain occurring near the nut. This indicates that this region is critical for energy absorption and potential failure initiation. U represents the displacement vector (m), while U2 represents the vertical displacement component (m). In addition, when element deletion is activated in ABAQUS, the progressive failure of the bolt can be more clearly visualised, as highly strained elements are removed and the overall deformation pattern becomes more apparent.

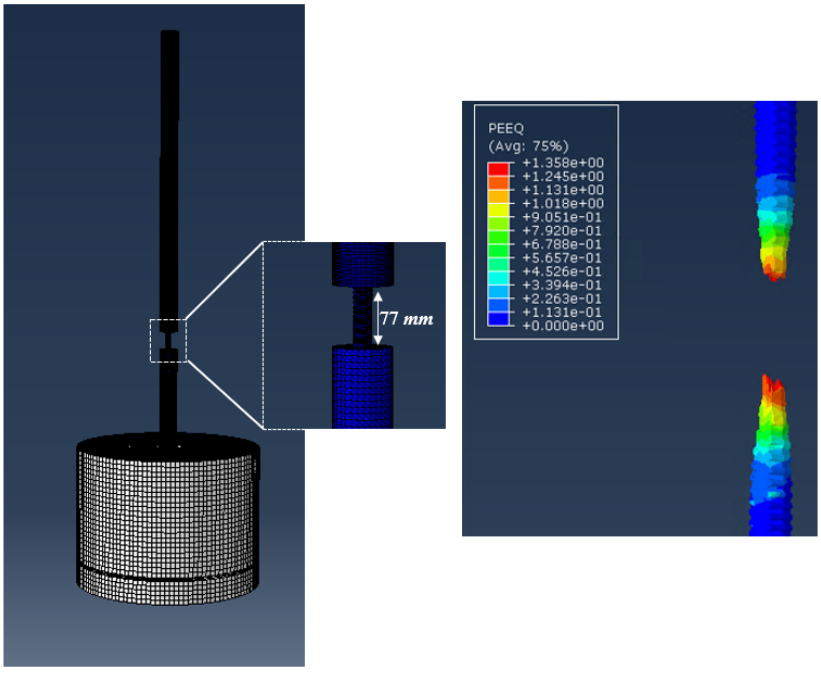


Figure 3 Failure mechanism of the reinforcement system

The finite element model (FEM) predictions showed good agreement with the experimental results, accurately reproducing the overall load–displacement response of the reinforcement system (Figure 4). The predicted peak load of approximately 350 kN closely matched the experimental value, demonstrating that the model can accurately capture the load-carrying capacity of the reinforcement system. Under an input energy of 32.6 kJ, the experimental dissipated energy ranged from 8.2 to 9.5 kJ, whereas the numerical model predicted 11.3 kJ (Table 3). Only this part of the energy is absorbed by the reinforcement elements through plastic deformation, while the rest is transferred to the surrounding materials and contact interfaces.

Table 3 Comparison of experimental Western Australian School of Mines (WASM) results (Villaescusa et al. 2015) and finite element model (FEM) simulation results

	Maximum force		Failure/maximum displacement		Discrepancies versus FEM (%)
	Displacement (mm)	Force (kN)	Displacement (mm)	Energy (kJ)	
WASM #170	16.2	346	34	8.2	27.4
WASM #171	13.8	350	40	9.5	15.9
FEM	12.1	354	36	11.3	–

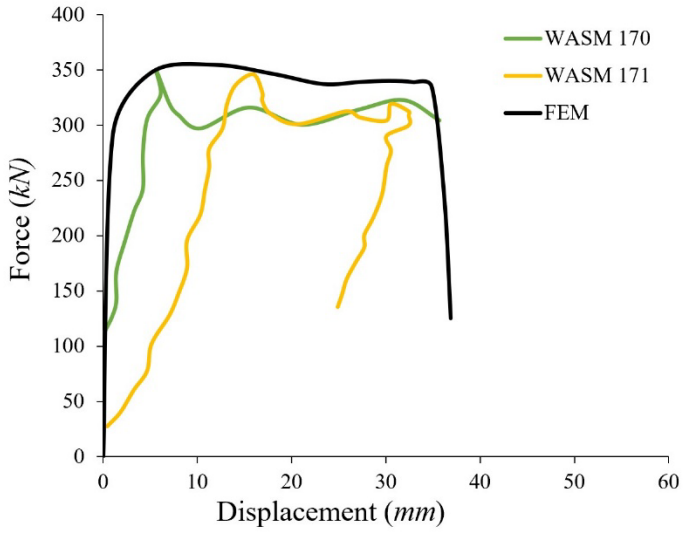


Figure 4 Dynamic load–displacement response for the reinforcement system

The numerical model slightly overestimated the dissipated energy compared with the experimental measurements. However, the predicted response remained in good agreement with the experimental behaviour. This difference may be attributed to the simplified representation.

4 Conclusion

The numerical results demonstrate that the developed ABAQUS model can accurately simulate the dynamic response of the reinforcement system under momentum–transfer loading. The FEM model captured the key features of the experimental load–displacement response, including the peak load of approximately 350 kN and the overall displacement behaviour. Although the numerical dissipated energy of 11.3 kJ was higher than the experimentally measured range of 8.2–9.5 kJ, the model reasonably represented the overall system

response. These results confirm that the developed numerical model provides a reliable basis for further investigation of reinforcement behaviour under dynamic loading and for numerically calibrating support systems. The validated approach can also be extended to more complex integrated ground support systems, improving understanding and design under rockburst conditions.

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