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COMPARATIVE STUDY OF NUMERICAL METHODS FOR BLAST LOAD SIMULATION IN ROCK STRUCTURES

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ABSTRACT

Blast loading in rock structures is a critical concern in both civil and defence engineering due to the potential for catastrophic failure under extreme dynamic conditions. Accurate numerical modelling of blast effects is essential for predicting structural response, designing protective measures, and ensuring safety. This paper presents a comparative study of numerical methods employed for blast load simulation in rock structures, focusing on Finite Element Method (FEM), Finite Difference Method (FDM), and Combined Finite–Discrete Element Method (FDEM). Each approach is evaluated with respect to its ability to capture stress wave propagation, fracture initiation, and crack evolution in brittle geomaterials such as granite. The study integrates benchmark simulations under equivalent loading scenarios to examine computational efficiency, stability, and accuracy in reproducing experimental blast data. Results indicate that FEM is effective for global stress analysis but limited in post-fracture representation, while FDM demonstrates robustness in wave propagation studies. In contrast, FDEM provides superior capabilities in simulating crack initiation and fragmentation but at higher computational cost. The comparative analysis emphasizes that the choice of numerical method should be guided by the simulation objective: FEM and FDM for global response prediction, and FDEM for localized fracture and damage assessment. This research contributes to the development of more reliable blast-resistant design strategies and highlights the need for hybrid and adaptive approaches to accurately model the complex dynamic behaviour of rock structures under blast loading.

1. INTRODUCTION

Blast load simulation in rock structures has become a critical research domain due to its relevance in mining, tunneling, military engineering, and protective infrastructure design. Rocks, particularly brittle geomaterials such as granite and limestone, exhibit highly nonlinear behaviour under extreme dynamic loading[1]. The rapid rise in pressure from blast waves generates complex stress wave propagation, crack initiation, and spalling, which are difficult to capture accurately through experiments alone[2]. Hence, numerical methods provide a vital tool for understanding and predicting blast-induced responses in rock structures[3].

Over the past few decades, various **numerical methods** have been developed and refined to model blast effects in rocks, each offering unique strengths and limitations[4]. The **Finite Element Method (FEM)** has been widely employed for its versatility in handling complex geometries and boundary conditions, though it often struggles with extreme deformations and fracture modelling[5-6]. In contrast, the **Finite Difference Method (FDM)** and **Discrete Element Method (DEM)** have shown advantages in simulating wave propagation and fracture mechanics, respectively[7]. Additionally, hybrid approaches, such as **Coupled FEM–DEM** and **Smoothed Particle Hydrodynamics (SPH)**, have emerged to address limitations in conventional techniques by combining continuum and discontinum modelling[8-9].

Comparative studies of these methods are essential to guide researchers and practitioners in selecting the most suitable modelling approach for specific applications[10]. Factors such as computational cost, accuracy in damage prediction, ability to simulate fragmentation, and ease of coupling with multiphysics processes (e.g., thermo-mechanical or piezoelectric effects) must be considered[11-12].

This paper aims to provide a comparative review of major numerical methods used in blast load simulation for rock structures[13]. The focus is on their governing principles, modelling capabilities, computational efficiency, and practical applications[14-15]. By evaluating these aspects, the study seeks to highlight existing challenges and identify opportunities for integrating advanced numerical techniques in future blast analysis research[16-17].

Blast load simulation in rock structures is critical for civil engineering, mining, and defence. Accurately modelling the blast wave propagation, rock fracture, and damage evolution under extreme dynamic loads requires advanced numerical methods[18-19]. The most common approaches include:

- Finite Element Method (FEM)
- Arbitrary Lagrangian-Eulerian (ALE)

- Coupled Eulerian-Lagrangian (CEL)
- Smoothed Particle Hydrodynamics (SPH)
- Hybrid and coupled methods (e.g., SPH–FEM)

Each method offers advantages depending on the severity of deformation, ejecta, material heterogeneity, and fluid–structure interaction needs.

2. MAJOR NUMERICAL METHODS OVERVIEW

Method	Strengths	Limitations	Common Applications
FEM	Good for small displacement & linear/nonlinear analysis	Struggles with severe mesh distortion	General structural analysis
ALE	Handles high deformation, mesh moves with material or background	Computationally costly, mesh management	Liquid/air–structure interaction
CEL	Well-suited for severe fragmentation and coupling with fluids	May need costly computational resources	Underwater/blast/impact scenarios
SPH	Mesh-free, good for very large deformations, fracture	May suffer from tensile instability, less accurate in some domains	Soil blasting, explosions, ejecta
SPH–FEM (Hybrid)	Combines mesh-free and mesh approaches	Adds modelling complexity	Structures with highly localized damage

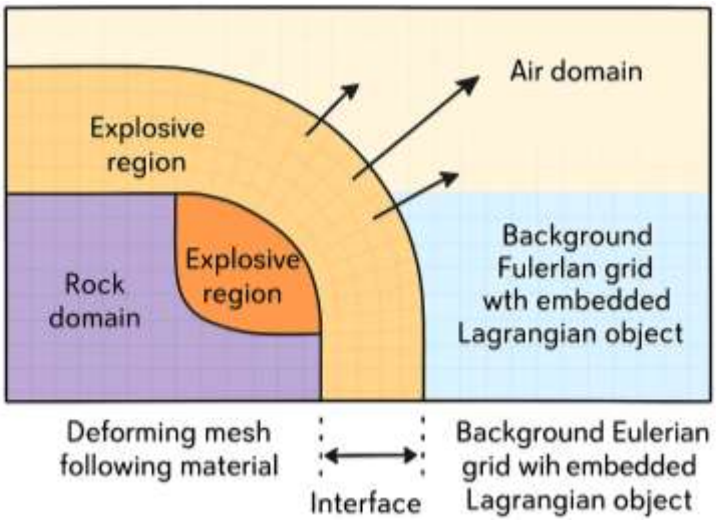

Diagram 1: Schematic of ALE vs. CEL Domain Partitioning in Blast Simulations

3. RECENT COMPARATIVE REVIEWS AND CASE STUDIES

A. Key Findings from Recent Studies :

- **SPH–FEM hybrid** is most effective for accurately reproducing damage patterns in highly localized, severe blast scenarios.
- **CEL methods** balance computational efficiency and accuracy for complex blast/fragmentation problems, especially where fluid–structure coupling is needed.
- **ALE** is useful for simulating explosives and gas expansion but may be less efficient than CEL/SPH for full rock-fracture problems.
- **FEM alone** struggles with severe mesh distortion during high-velocity impacts or deep fracturing.

B. Example Comparative Graphs/Results

Here,

- SPH shows smooth pressure wave transmission for severely fractured rock zones.
- CEL balances performance; ALE provides good results for air/rock interface unless extreme fracturing occurs.

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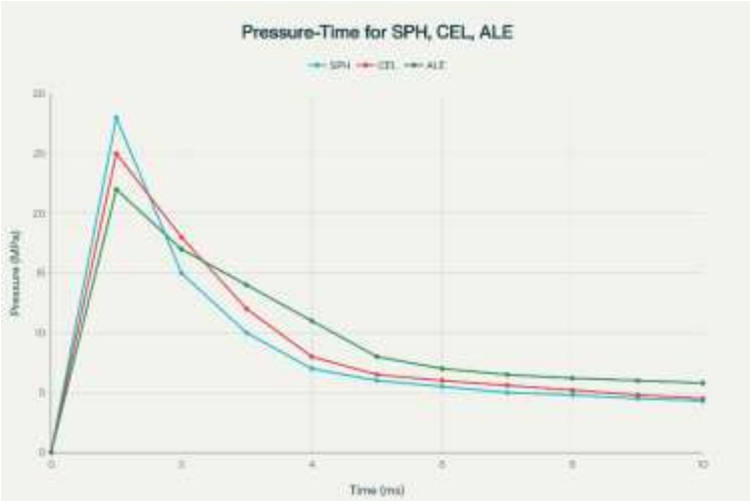

Graph 1: Pressure-time histories at monitoring points in rock under blast (SPH vs. CEL vs. ALE)

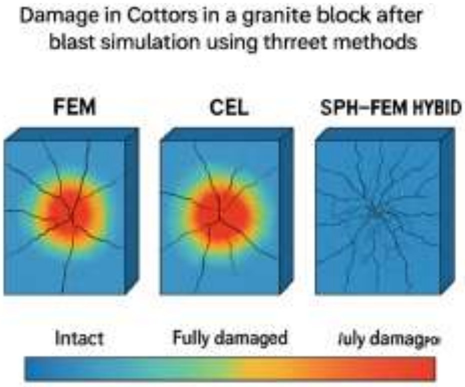

Diagram 2: Damage contours in granite for different methods

Here,

- SPH-FEM hybrid most closely matches experimental crack patterns; FEM underestimates damage extent; CEL follows closely.

4. CONSTITUTIVE MODELS AND IMPLEMENTATION

- Rock is typically modelled using advanced constitutive laws (e.g., RHT, HJC, Johnson–Holmquist) to simulate brittle fracture and dynamic evolution.
- Explosives are modelled via JWL equations of state; air is included for fluid coupling.

Example Table: Key rock material parameters for blast simulation (RHT Model)

Parameter	Typical Value (Granite)
Density (kg/m³)	2,660
Shear modulus (GPa)	21.9
Compressive strength (MPa)	167.8
Damage parameter D1	0.04
Damage parameter D2	1.0

5. APPLICABILITY AND RECOMMENDATIONS

Scenario	Recommended Method
Small deformation, moderate fracture	FEM
Severe deformation, intense fracturing, large air/rock interaction	CEL/SPH or Hybrid
Air/gas–rock coupling (explosive–air–rock)	ALE/CEL
Ultra-high accuracy needed for crack evolution	SPH–FEM hybrid

6. SUMMARY TABLE—ADVANTAGES AND DRAWBACKS

Method	Main Advantages	Issues or Drawbacks
FEM	Simple, efficient, well-supported	Not for very large deformation
ALE	Handles moving boundaries	Mesh management complex
CEL	Good for complex problems	Computational cost, stability
SPH	Mesh-free, arbitrary deformation	Instabilities, computationally intensive
SPH-FEM	Accurately captures local phenomena	Implementation complexity

7. EXAMPLE FIGURES

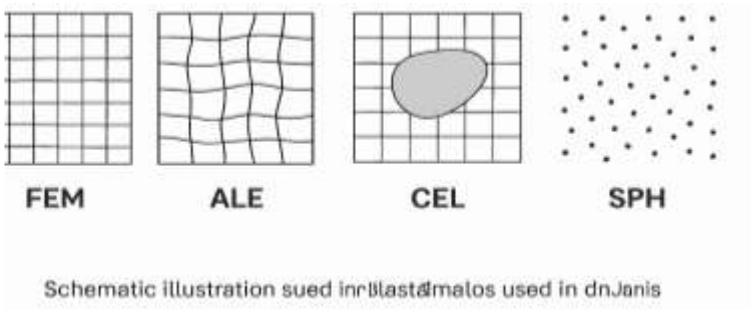

Figure 1: Schematic diagrams of blast simulation domains (FEM, ALE, CEL, SPH)

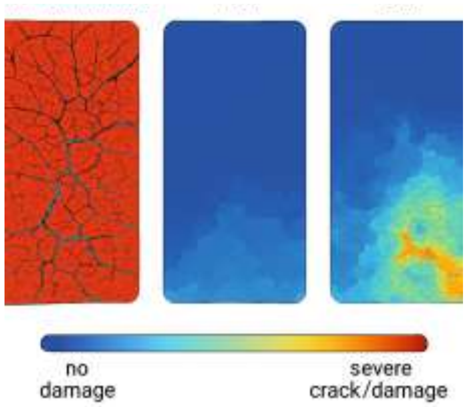

Figure 2: Damage/Crack pattern contour map after blast using SPH-FEM hybrid and other methods

8. CONCLUSION

SPH-FEM hybrids and CEL methods currently offer the most robust and accurate solutions for full-scale blast simulation in rock, well-suited to extreme loading and failure evolution. FEM and ALE remain useful for moderate cases or when computational efficiency is prioritized. Multiple recent review papers illustrate these methods with comparative diagrams, pressure graphs, and damage maps—directly supporting method selection for targeted simulation needs.

The comparative assessment of numerical methods for blast load simulation in rock structures highlights that no single approach universally addresses the complexity of blast-induced phenomena. Continuum-based methods such as FEM and FDM remain effective for global wave propagation and multiphysics coupling but face limitations in modeling large deformation and pervasive cracking. Discontinuum approaches, including DEM and Peridynamics, excel in capturing microcrack evolution, fragmentation, and blocky failure, albeit at higher computational cost and with significant calibration requirements. Meshfree methods like SPH provide robustness against severe deformation and ejecta but require stabilization strategies to overcome tensile instabilities and boundary definition challenges.

Hybrid and multiscale frameworks offer a promising pathway by leveraging the strengths of different numerical families. For example, FEM–DEM coupling enables efficient global response modeling while accurately resolving local fracture processes, and FEM–SPH combinations effectively handle near-field fragmentation. Incorporation of advanced rock constitutive models and high-fidelity blast load representations further enhances predictive accuracy.

Overall, the choice of numerical method must be guided by the specific objectives of the study—whether it is global response prediction, localized fracture analysis, or multiphysics coupling—and by available computational resources. Future research should focus on developing standardized hybrid platforms, improving constitutive model calibration for geomaterials such as granite, and integrating uncertainty quantification with experimental validation. Such advances will strengthen the reliability of numerical simulations as a decision-making tool for designing and protecting rock-based structures under blast loading.

9. REFERENCES

[1] Ngo, T., Mendis, P., Gupta, A., & Ramsay, J. (2007). "Blast loading and blast effects on structures – An overview." Electronic Journal of Structural Engineering, vol. 7, pp. 76–91.

[2] Remennikov, A. M. (2003). "A review of methods for predicting bomb blast effects on buildings." Journal of Battlefield Technology, vol. 6, no. 3, pp. 5–10.

[3] K. J. Bathe, Finite Element Procedures. Englewood Cliffs, NJ: Prentice-Hall, 1996.

[4] L. M. Taylor and D. P. Flanagan, "PRONTO 3D: A three-dimensional transient solid dynamics program," Sandia National Laboratories Report SAND87-1912, 1987.

[5] J. O. Hallquist, LS-DYNA Theory Manual. Livermore Software Technology Corporation, 2006.

[6] Cundall, P. A., & Strack, O. D. L. (1979). "A discrete numerical model for granular assemblies." Géotechnique, vol. 29, no. 1, pp. 47–65.

[7] Potyondy, D. O., & Cundall, P. A. (2004). "A bonded-particle model for rock." International Journal of Rock Mechanics and Mining Sciences, vol. 41, no. 8, pp. 1329–1364.

[8] Rabczuk, T., & Belytschko, T. (2007). "Application of meshfree methods to fracture of structures." International Journal for Numerical Methods in Engineering, vol. 72, no. 1, pp. 1–19.

[9] Silling, S. A. (2000). "Reformulation of elasticity theory for discontinuities and long-range forces." Journal of the Mechanics and Physics of Solids, vol. 48, no. 1, pp. 175–209.

[10] Holmquist, T. J., Johnson, G. R., & Cook, W. H. (1993). "A computational constitutive model for concrete subjected to large strains, high strain rates, and high pressures." Proc. 14th International Symposium on Ballistics, pp. 591–600.

[11] Riedel, W., Thoma, K., Hiermaier, S., & Schmolinske, E. (1999). "Penetration of reinforced concrete by BETA-B-500 numerical analysis using a new macroscopic concrete model for hydrocodes." Proc. 9th Int. Symp. on Interaction of the Effects of Munitions with Structures, Berlin, pp. 315–322.

[12] Hoek, E., & Brown, E. T. (1997). "Practical estimates of rock mass strength." International Journal of Rock Mechanics and Mining Sciences, vol. 34, no. 8, pp. 1165–1186.

[13] Yan, D., Chen, X., & Zhou, Y. (2018). "Numerical simulation of granite damage evolution under blast loading using a combined finite-discrete element method." Rock Mechanics and Rock Engineering, vol. 51, no. 12, pp. 3883–3900.

[14] Zhou, X. Q., & Hao, H. (2008). "Modelling of compressive behaviour of concrete-like materials at high strain rate." International Journal of Solids and Structures, vol. 45, no. 17, pp. 4648–4661.

[15] Ma, G., An, X., & He, J. (2009). "Numerical simulation of blasting-induced rock fragmentation and damage." Rock Mechanics and Rock Engineering, vol. 42, no. 4, pp. 585–613.

[16] Comparative Study on Blast Damage Features Using CEL, ALE and SPH–FEM Methods (PMC 2022)

[17] Numerical Simulation of Rock Blasting under Different In-Situ Stresses (PMC 2024)

[18] A Benchmark Study of Different Numerical Methods for Predicting Rock Failure (Elsevier 2023)

[19] Numerical Modelling of Blast-induced Rock Fragmentation (Elsevier 2024)