

Numerical modeling of brittle mineral foam in a sacrificial cladding under blast loading

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Received: 28 February 2023 / Accepted: 26 June 2023

Abstract. Cellular materials, such as aluminum foams, have proven to be excellent energy absorbers. They can be used as crushable core in sacrificial cladding (SC) for blast load mitigation. In this study, the blast absorption capacity of a brittle mineral foam-based SC is investigated through finite element modeling using the LS-DYNA software. The experimental set-up used consists of a rigid steel frame with a square cavity of 300 mm x 300 mm in the center. The structure to be protected is simulated by a thin aluminum plate clamped into the rigid steel frame. The blast load is generated by 20 g of C4 high explosive set at a distance of 250 mm from the center of the plate. The blast absorption capacity of the considered SC is evaluated by comparing the maximum out-of-plane displacement of the center of the plate with and without the protective brittle mineral foam. The presence of the brittle mineral foam reduces the maximum out-of-plane displacement of the center of the plate at least by a factor of two. The brittle mineral foam is modeled both in solid elements and smoothed-particle hydrodynamics (SPH) by using Fu Chang's constitutive material law based exclusively on the results of quasi-static compression tests of the foam and a phenomenological relationship between stress, strain and strain rate. The SPH model predicts the maximum out-of-plane displacement of the center of the aluminum plate with an average relative error of 5% with respect to the experimental values.

Keywords: Blast loading / brittle mineral foam / sacrificial cladding / numerical modeling

1 Introduction

In recent years, there has been a substantial increase in the use of improvised explosive devices in terrorist attacks on civil engineering structures [1]. The blast waves generated during an explosion are accompanied by large pressures build-up over a relatively short time [2]. These large pressures can cause damage to both humans and infrastructure. To reduce the impacts of blast loads on structures and to assure their survival, it is essential to adopt strengthening or protective techniques. Reinforcing structural components is the traditional technique of protection [3–5]. However, the idea of using foams as crushable cores in sacrificial cladding (SC) solutions have been the subject of numerous studies in the world of protective engineering [6–13]. Foams have the ability to undergo large deformations under constant low stress compared to the strength of the protected structure [14]. They are generally characterized by a stress-strain curve subdivided into three regions: (i) a linear elastic region, (ii)

the plateau stress region with permanent crushing of the foam cells under quasi-constant loading, and (iii) the densification region after the collapsing of the entire cell structure. A sacrificial cladding consists of a crushable material positioned in between the structure to be protected and a front plate [15]. The purpose of this front skin is to distribute the generated blast pressure to the crushable core and ensure its uniform compression [16].

Crushable cores such as aluminum foam [6,8,11,12,17,18], polymeric foam [13,15,19,20] and honeycomb structures [7] among others are intensively studied in literature. Wu et al. [18] used an aluminum foam-based sacrificial cladding to mitigate blast effects on a simply supported RC slab. They assessed the effectiveness of the aluminum foam to protect the slab based on an adapted single degree of freedom model supported by a full-scale experiment. It was shown that the aluminum foam was not completely compacted and that the cracks in the concrete are substantially present through the depth and along the length of the slab. The obtained results were explained by the higher plateau stress transmitted to the main structure. To ensure effective structural protection, the plateau stress of the crushable core should be correctly selected to match

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the resistance of the main structure, according to the analytical Load-Cladding-Structure (LCS) model proposed by Ma et al. [21]. From the Facility And Component Explosive Damage Assessment Program (FACEDAP) database [22], the resistance of structural components in conventional buildings (divided by the loaded area) ranges between 60 and 500 kPa. Therefore, aluminum foams with a plateau stress range of 1–20 MPa are unsuitable. Polymeric and mineral foams on the other hand present lower plateau stress. Ousji et al. [15] studied blast loading attenuation using a polyurethane (PU) foam-based sacrificial cladding. The effect of the front plate mass and the foam properties were investigated in multiple combinations. It was found that the absorption capability was improved by increasing the front plate mass, the plateau stress, and the thickness of the PU foam. Blanc et al. [9] worked on the efficiency of sacrificial cladding with brittle materials, from concrete foam to granular media, for blast mitigation using an explosive driven shock tube. It was observed that brittle materials can efficiently act as a crushable core. Jonet et al. [10] showed the potential of a brittle calcium-silicate based-mineral foam as a crushable core in a SC for blast mitigation. Very limited investigations on dynamic response of brittle mineral foams under high rate loadings such as blast and impact can be found in the literature [23–25]. Forquin [24] showed that the dynamic testing techniques based on the used of split Hopkinson pressure bar (SHPB) and/or plate-impact testing methods have some critical limitations and drawbacks when used to investigate the behavior of brittle materials at high strain rates. It was proposed new processing technique based on the virtual fields method (VFM) in combination with an ultra-high-speed camera and compact pulsed power generator to measure the mechanical properties of the material. These techniques have proven to be effective. However, they are complex and costly. Therefore, there is a tendency among numerous researchers in this field to overstate the impact of strain rate on brittle materials [17]. In their investigation, Janszen et al. [26] examined the effectiveness of carbon foam in stopping small fragment impacts. Two carbon foams with densities of 560 kg/m^3 and 240 kg/m^3 were utilized. The fragment was simulated using a 5 mm diameter stainless steel sphere fired at a velocity of up to 240 m/s by a compressed air gun. Since it was not possible to test and measure the dynamic properties of the materials under high strain rate loading conditions, a phenomenological relationship between compressive strength and strain rate was utilized to model the material behavior. This relationship was incorporated into an LS-DYNA material model, which was then used to simulate the ballistic experiments.

The purpose of this work is to improve the numerical modeling of the proposed sacrificial cladding in [10] for the first setup. This setup consists of an aluminum plate clamped on all four sides within a fixed rigid steel frame, allowing for the evaluation of the blast-mitigating efficiency of the foam core by comparing the deflection magnitude of the aluminum plate with and without the foam-based protection. To model the brittle mineral foam,

two types of modeling methods are proposed: a solid elements method and a meshless approach using Smoothed Particle Hydrodynamics (SPH). The commercial software LS-DYNA is utilized for this purpose.

The structure of the paper is as follows: In Section 1, the context and the state-of-the-art for sacrificial cladding under blast load are surveyed. In Section 2, the background of the work is first stated. Then, the finite element modeling is described including the loading, the modeling method, and the material models and the obtained results are discussed. At last, the conclusions are formulated in Section 3.

2 Numerical modeling of brittle mineral foam

2.1 Background

2.1.1 Experimental campaign set-up

The SC (Fig. 1) consists of (i) a thin 2 mm thick aluminum backplate (EN AW-1050 H24) representing the structure fixed on a rigid metal frame with a free surface of $300 \times 300 \text{ mm}^2$, (ii) a 60 mm thick brittle mineral foam with dimensions $300 \times 300 \text{ mm}^2$ and (iii) a second aluminum plate serving as a front plate. The protected aluminum plate is painted with a speckle pattern to measure the transient deformation fields by using three-dimensional digital image correlation (3D-DIC) technique (Fig. 1a). The foam samples are characterized by a cross-section of $300 \times 300 \text{ mm}^2$ (cut from panels with a thickness of 60 mm). The resultant stand-off distance (between the explosive charge and the front skin) is 188 mm, taking into account the thickness of 2 mm of the aluminum front plate.

The absorption capacity of the brittle mineral foam is assessed by comparing the out-of-plane displacement of the center of the clamped aluminum plate with and without the mineral foam under a blast loading. The blast load is generated by 20 g of C4 set at 250 mm from the center of the structure. In order to evaluate the reproducibility, each test per configuration is performed three times. Figure 2 shows the obtained experimental out-of-plane displacements. The displacement is reduced from $21.7 \pm 0.7 \text{ mm}$ without the foam to $11.7 \pm 0.1 \text{ mm}$ with the foam, i.e., a reduction of 46%. The distance between the charge and the structure is kept constant. Therefore, adding the foam increases the reflected pressure and impulse from 7.94 MPa and 0.20 MPa ms to 16.86 MPa and 0.30 MPa ms, respectively.

The foam used in this work is closed-cell micro-structure foam based on brittle mineral materials. It has a density of 110 kg/m^3 and a porosity of 95%. The foam is a mixture of calcium silicate hydrate (70–80% w/w), quartz (<2% w/w), calcite (15–20% w/w) and gypsum (3–8% w/w) that is stabilized in an autoclave under a pressure of 12 bar and a temperature of about 190 °C. From three uni-axial quasi-static compression tests (Fig. 3), i.e. using a displacement velocity of 1 mm/min, the following mechanical properties are found: Young's modulus of $30 \pm 2 \text{ MPa}$, a plateau stress of $237 \pm 11 \text{ kPa}$, and a densification strain of $72 \pm 1\%$.

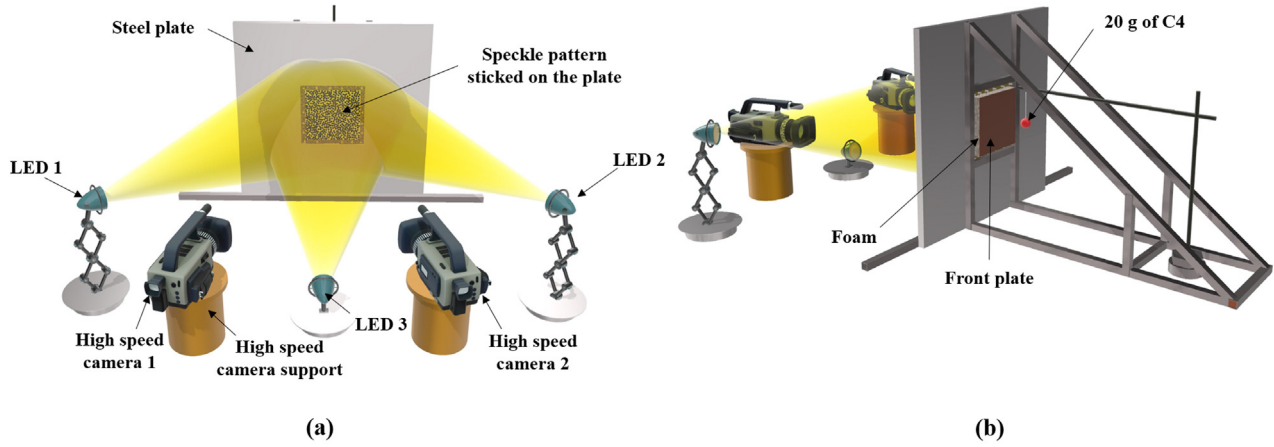


Fig. 1. (a) Front view and (b) side view of the experimental set-up inspired by [10].

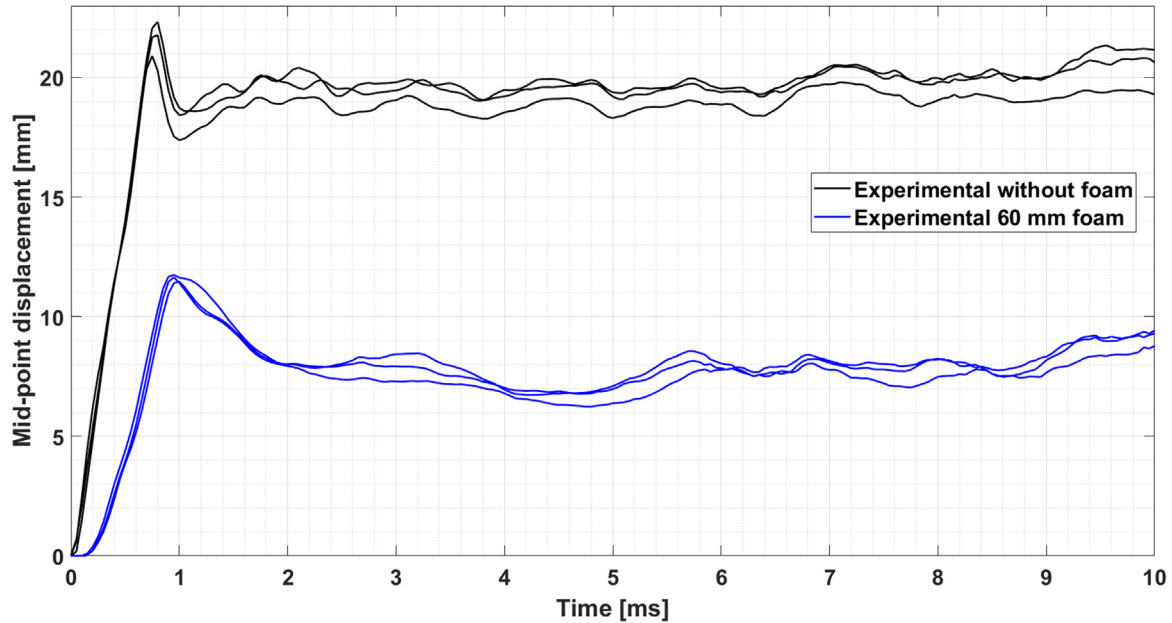


Fig. 2. Experimental out-of-plane displacements measured by DIC with and without the foam.

2.2 Finite element modeling

2.2.1 Blast load model

Blast loading simulation in LS-Dyna R10.0 (double precision mode) can be performed using either Eulerian approach or an empirical model for blast pressure approximation. In the first approach the time and space distribution of the blast pressure profile are computed through a Eulerian mesh by means of the equation of state (EOS) for high explosives. This approach is time-consuming compared to that of the use of empirical models. The second approach is adopted for far and intermediate explosions. The blast pressures are computed based on the empirical formulae developed by Kingery and Bulmash and implemented by Randers-Pehrson and Bannister [27] in

LS-DYNA (*LOAD_BLAST_ENHANCED* card). The empirical data for air burst are valid for the range of scaled distance Z situated between $0.147 \text{ m/kg}^{1/3}$ and $40 \text{ m/kg}^{1/3}$ where $Z = R/M^{1/3}$, R is the distance from the charge center to the target and M is the TNT equivalent mass of the charge [27]. For the studied configuration, Z is $0.642 \text{ m/kg}^{1/3}$ with the protective sacrificial cladding and $0.855 \text{ m/kg}^{1/3}$ without the protection. Therefore, the second approach is retained in this case.

2.2.2 Modeling method

As illustrated in Figure 4, the complete set-up is taken into account for the numerical modeling using a Lagrangian formulation. The steel frame is modeled using $5 \text{ mm} \times 5$

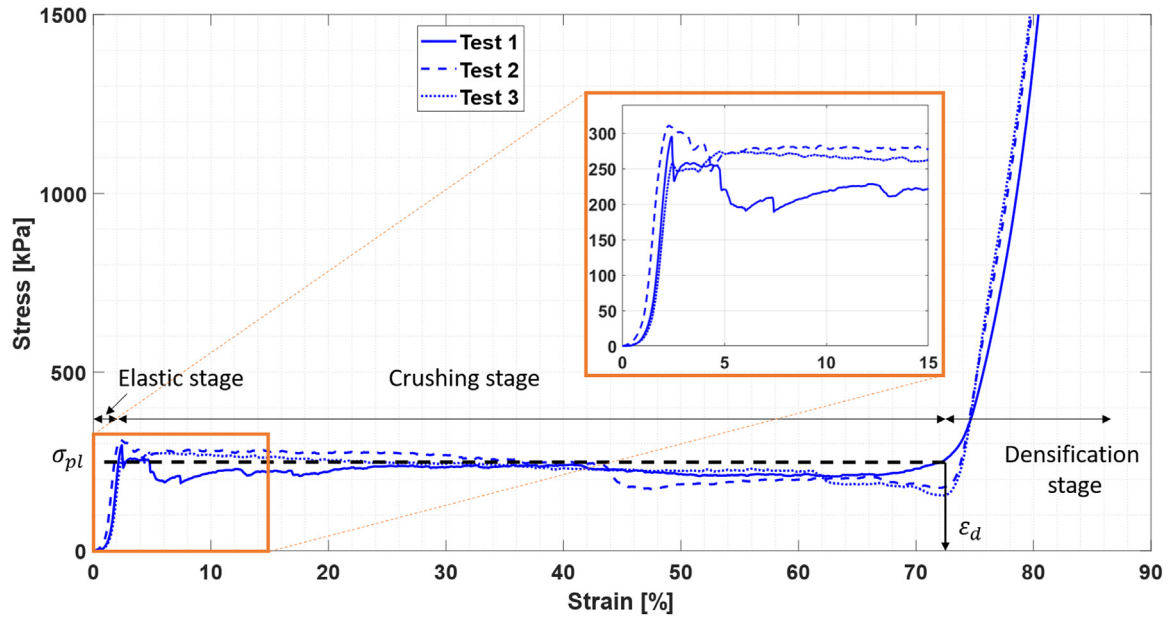


Fig. 3. Quasi-static compression stress-strain curves for brittle mineral foam, obtained from three tests on samples sized $160 \times 160 \times 60 \text{ mm}^3$, revealing its mechanical behavior under compressive loading conditions.

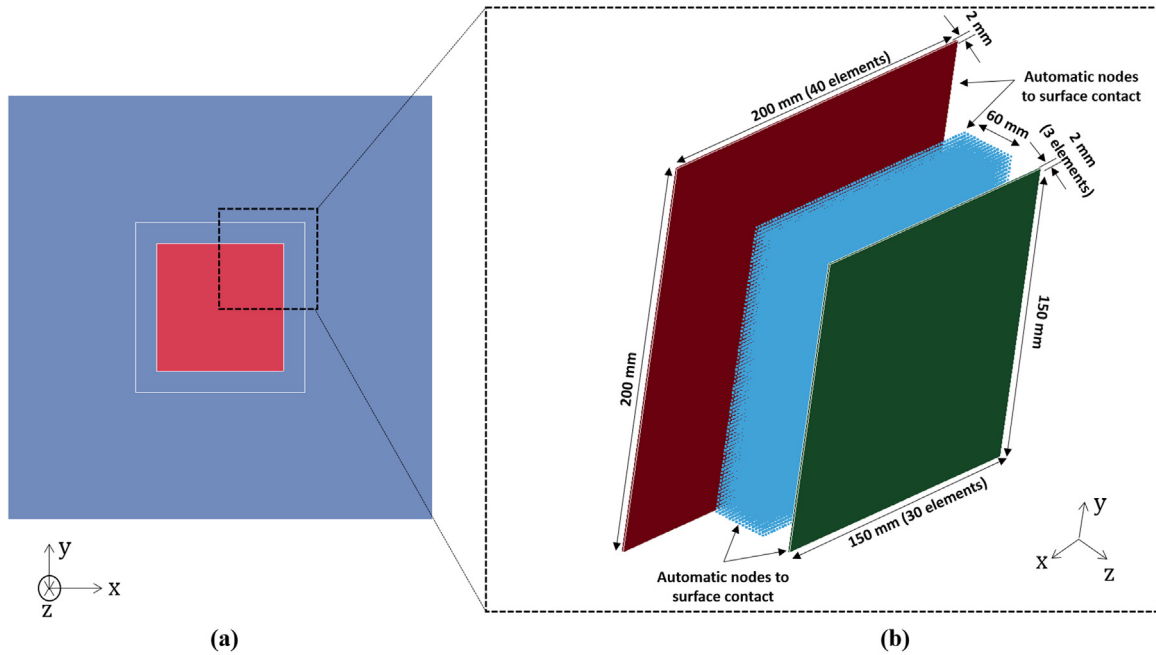


Fig. 4. (a) Full FE modeling of the set-up and (b) FE model of the sacrificial cladding solution with the foam in SPH.

mm $\times$ 1.95 mm shell elements (Belytscko-Li-Tsay) while 5 mm $\times$ 5 mm $\times$ 0.67 mm Fully Integrated S/R Solid Elements (ELFORM-2) were used for all aluminum components, i.e., the front plate and the backplate. The 60 mm brittle mineral foam is modeled using both traditional Lagrangian models and SPH particles. The meshless approach of SPH has proven to be more robust for high compaction and high dislocation applications [28,29].

The element size and the number of SPH particles are selected after a mesh convergence study (Fig. 5). The convergence study is in a first instance done for the aluminum plate, i.e., blue dashed line in Figure 5. Once the element size for the aluminum is fixed, the foam is added for a second convergence study, i.e., red dashed line in Figure 5. All degrees of freedom for the foam and the front plate nodes are unconstrained.

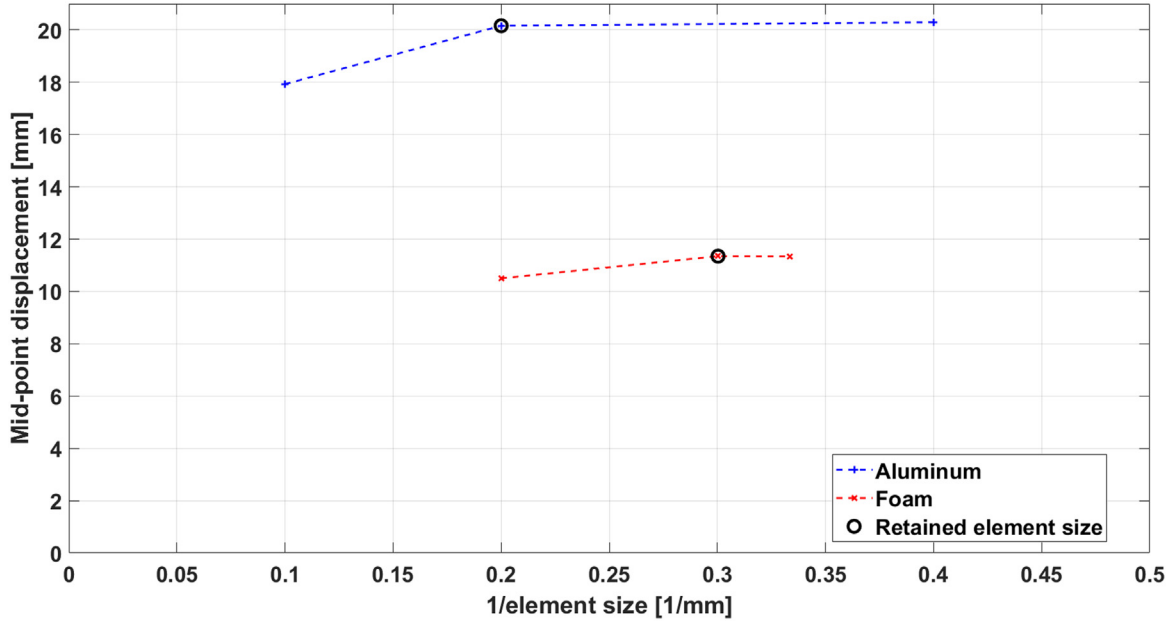


Fig. 5. Convergence study of the mesh size on the aluminum plates and the mineral foam.

AUTOMATIC_NODES_TO_SURFACE and TIED_SURFACE_TO_SURFACE contacts with a soft constraint formulation, which is recommended for cases with a large difference in elastic bulk modulus (Foam/Aluminum), were defined between all aluminum components and the foam respectively when using SPH and the Lagrangian formulation [7].

2.2.3 Material modeling

To describe the dynamic response of the different finite element parts, appropriate assumptions of the material behavior are necessary. From experimental results, it is observed that both the rigid steel frame and the clamping plate remain in the elastic region during the whole process. Consequently, a linear elastic constitutive law (*MAT 1) is used to model them. All parameters of the material model adopted for steel components are gathered in Table 1.

The aluminum plates undergo large deformations due to the intense blast loading. The strain rate effect is taken into account. Therefore the modified Johnson-Cook constitutive law (*MAT 107) is chosen. It takes into account strain hardening, strain rate, and thermal softening. The equivalent yield stress depending on the strain, strain rate and temperature is given by:

$$\sigma_y = \left[A + B\epsilon^n + \sum_{i=1}^2 Q_i (1 - \exp(-L_i \epsilon)) \right] \left(1 + C \ln \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \right) \left(1 - \left(\frac{T - T_a}{T_f - T_a} \right)^m \right) \quad (1)$$

where A , B , C , m , n , Q_1 , L_1 , Q_2 , L_2 are material parameters; ϵ is the plastic strain rate; $\dot{\epsilon}_0$ is the quasi-static threshold strain rate; T_a and T_f are the ambient and fusion temperatures, respectively. The parameters used for the

Table 1. Material model parameters for steel [10].

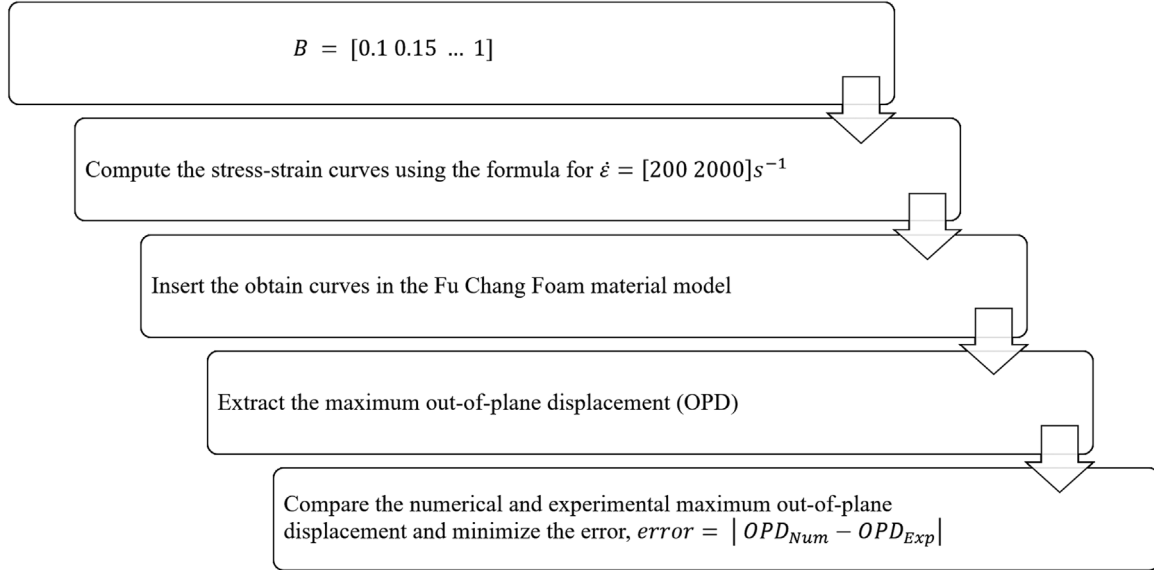
ρ [kg/m ³]	E [GPa]	ν [-]
7850	210	0.3

modified Johnson-Cook model are listed in Table 2 based on existing literature [30].

Constitutive models for foams such as Low Density Foam, Crushable Foam, and Fu Chang Foam have been proposed in the past [28,29]. The present study adopts the Fu Chang Foam model. This material model is a one-dimensional constitutive model due to the assumption of zero Poisson's ratio. The model allows a choice of uni-axial or tri-axial compression strain. It takes into account strain rate effects for uni-axial compression. It is worth noting that the characterization of strain-rate in cellular materials is a complex matter. It is generally acknowledged that the structural behavior resembles that of a conventional material. As emphasized by [23,24], this definition of strain-rate is suitable for quasi-static investigations of the material, as long as the elastic limit is not surpassed. However, when it comes to dynamic conditions, particularly for brittle materials, this definition becomes inapplicable. Conducting dynamic tests on brittle materials presents significant challenges, and the traditional approach involving SHPB is unsuitable, making it difficult to incorporate the dynamic increase factor [24]. Consequently, many researchers in this field tend to overstate the influence of strain-rate in brittle materials [17]. In this study, it is assumed a phenomenological relationship between the compressive strength σ and strain-rate $\dot{\epsilon}$ (Eq. (2)). Therefore, stress-strain curves are generated. This formula has been used for brittle materials,

Table 2. Material model parameters for aluminum [10].

ρ [kg/m ³]	E [GPa]	ν [-]	XS1 [-]	C_p [J/kg K]	α [/K]	$\dot{\epsilon}_0$ [s ⁻¹]	T_0 [K]
2710	69	0.33	0.9	899	$1.2e^{-5}$	1	293
A [GPa]	B [GPa]	n [-]	C [-]	Q_1 [GPa]	L_1 [-]	Q_2 [GPa]	L_2 [-]
0.065	0.014	0.36	0.014	0.025	3324	0.019	533

**Fig. 6.** Flowchart for B computation by inverse approach.

such as the mineral foam [26,31].

$$\sigma = \sigma_{qs} + B\dot{\epsilon}^N \quad (2)$$

where σ_{qs} is the quasi-static stress, N and B are material constants. N is equal to 1/3 for almost all brittle materials. B is computed by inverse approach as explained in Figure 6. Referring to the measured quasi-static compression curves, different stress-strain relationships varying the B parameters of equation (2) were computed covering a range of strain rate values. According to [32], strain rates range between 100 s⁻¹ and 10000 s⁻¹. Sun et al. [17] found strain-rates up to 1500 s⁻¹ for cellular materials. Therefore in this study, the considered strain-rates range from 200 s⁻¹ to 2000 s⁻¹ (Fig. 7).

Once a good correlation between experimental out-of-plane displacement and the value resulting from the analysis with the standard mesh was established, the B parameter was then fixed. The optimal B value found was 0.15 MPa. It is worth noting that a similar approach was employed in a previous study [26], which investigated carbon foams with densities of 240 kg/m³ and 560 kg/m³. Values of 0.28 MPa and 1 MPa were obtained for the B parameter, respectively. The parameters used to simulate the mineral foam using the Fu Chang Foam are summarized in Table 3.

2.3 Discussion of the results

2.3.1 Results from the numerical simulations

The computed and experimental out-of-plane displacements of the center of an aluminum plate with and without mineral foam protection are shown in Figure 8. The Lagrangian model of the foam underestimates the maximum out-of-plane displacement with a mean relative error of 40%. The SPH model predicts the out-of-plane displacement compared to the experimental results with relative errors between 3% and 7%. Hence, only the results from the SPH approach are discussed in the following.

Figure 9 shows the backplate deformation profile along the x-axis with the 60 mm thick foam and without the foam. It is noticeable that the shape of the deformation without the foam is approximating a rectangular shape in the first 0.4 ms and evolves into a dome-shaped profile after 0.6 ms. The profiles appear symmetrical to the center of the plate. The deflection peak is found to be in the central region. When the foam is added, the same rectangular then sinusoidal shapes are observed but with a delay corresponding to the time needed for the blast wave to go through the foam core.

2.3.2 Foam mechanism of absorption

The foam mechanism of blast loading absorption (Fig. 10) is analyzed by examination of the out-of-plane

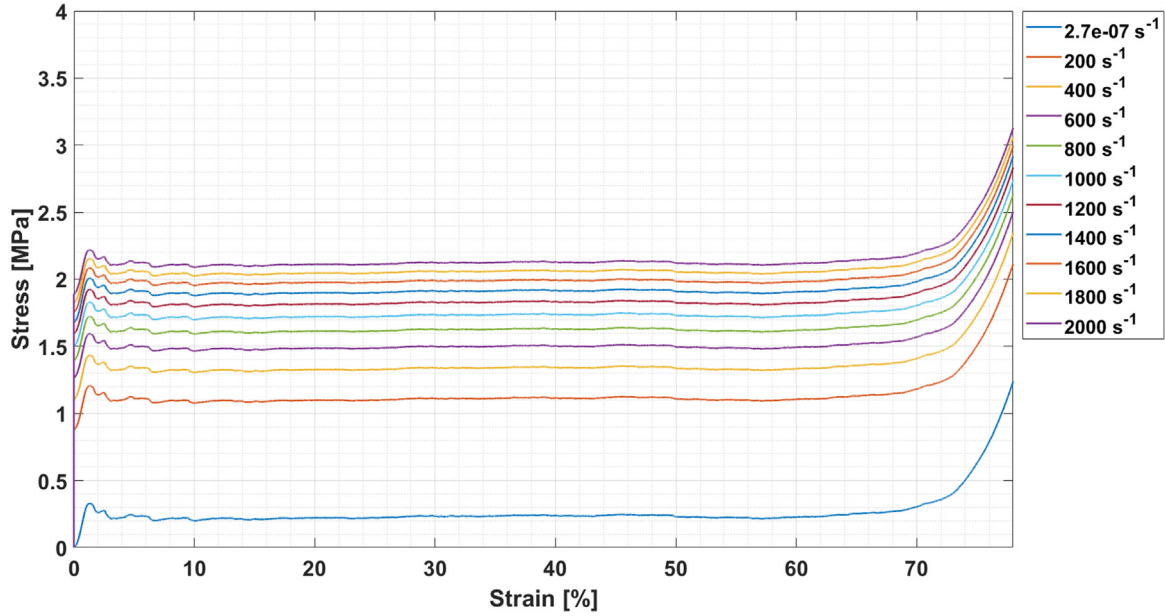


Fig. 7. Quasi-static and dynamic stress-strain curves as inputs for Fu Chang Foam material model.

Table 3. Material model parameters for the mineral foam.

ρ [kg/m ³]	E [MPa]	Table for stress vs. strain data as a function of strain rate
110	30	Cf. Figure 7

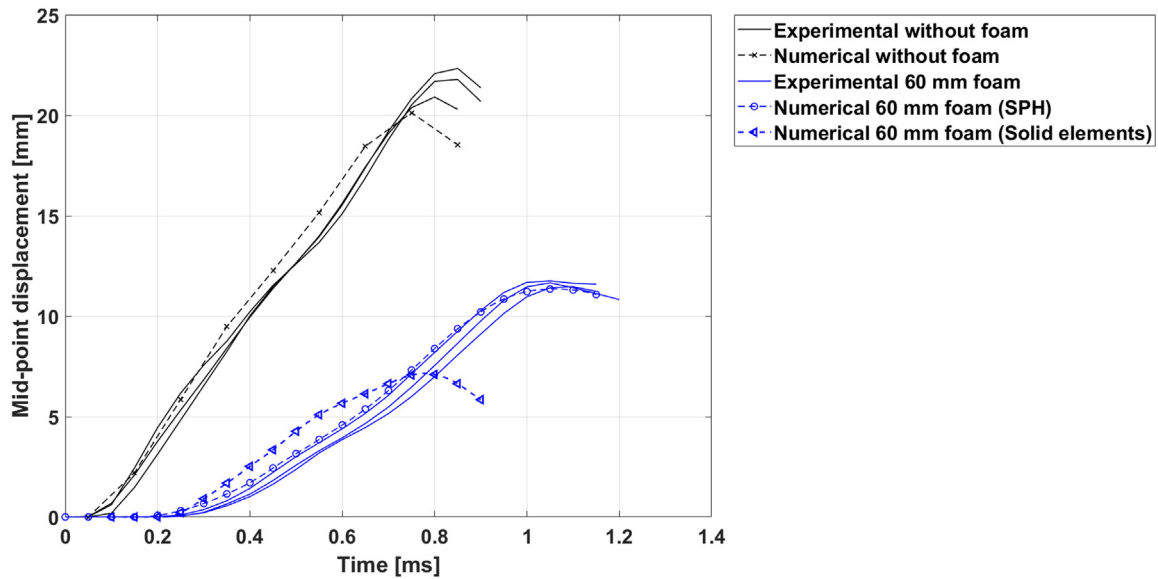


Fig. 8. Comparison between experimental and numerical out-of-plane displacements with and without the protective foam.

displacement field at different times: 0.2 ms, 0.3 ms and 1.1 ms corresponding respectively to the time the foam starts crushing, the time after the crushing starts, and the time when the maximum out-of-plane displacement is reached.

At 0.2 ms, the loading on the front plate is localized. The applied impulse yields a maximum velocity of the front plate of 49.7 m/s, i.e., $\dot{\epsilon} = 828 \text{ s}^{-1}$, which initiates the propagation of a compaction wave through the foam in the thickness direction. Almost the entire foam volume starts

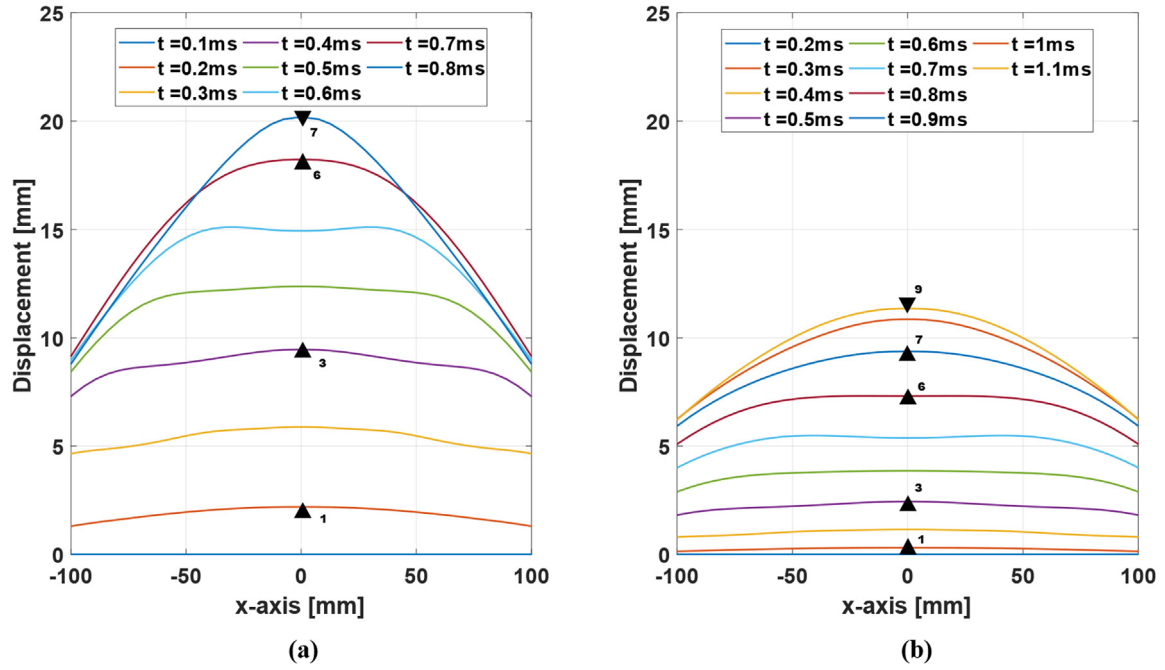


Fig. 9. Out-of-plane displacement profile at the center of the backplate along the x -axis (a) without foam and (b) with 60 mm thick foam layer.

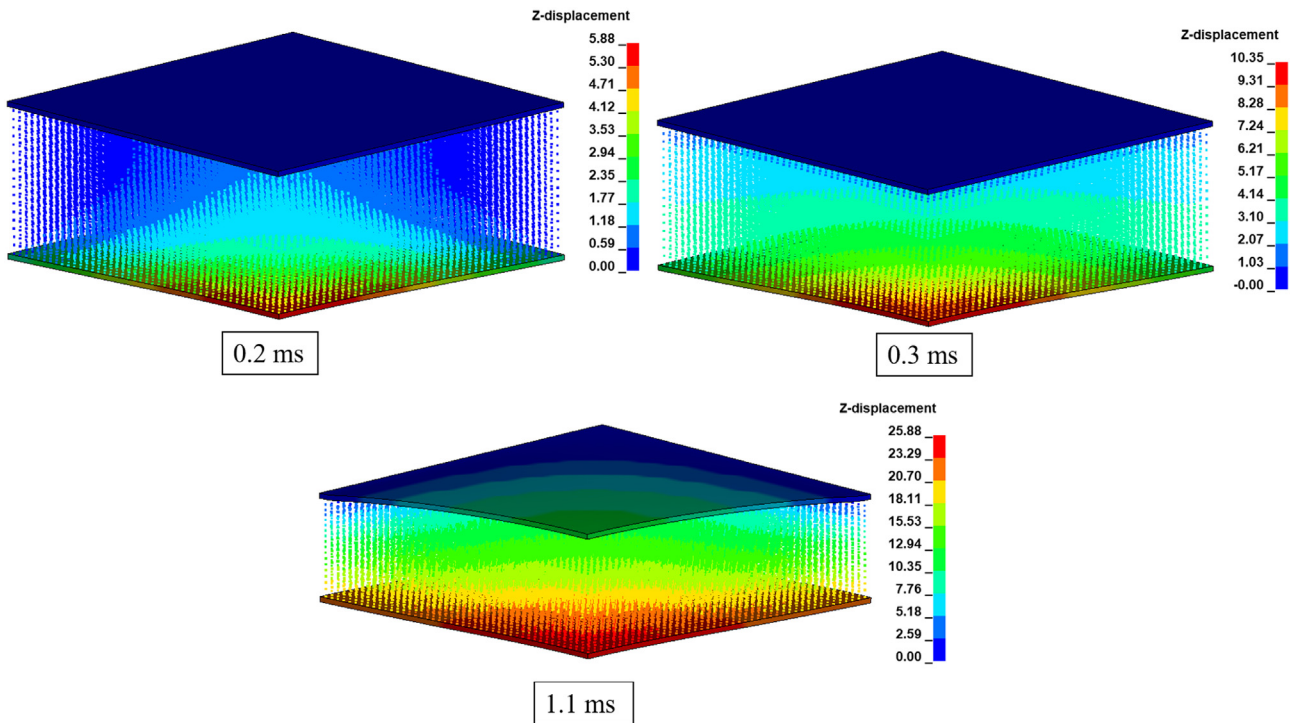


Fig. 10. Foam blast absorption mechanism at different time steps.

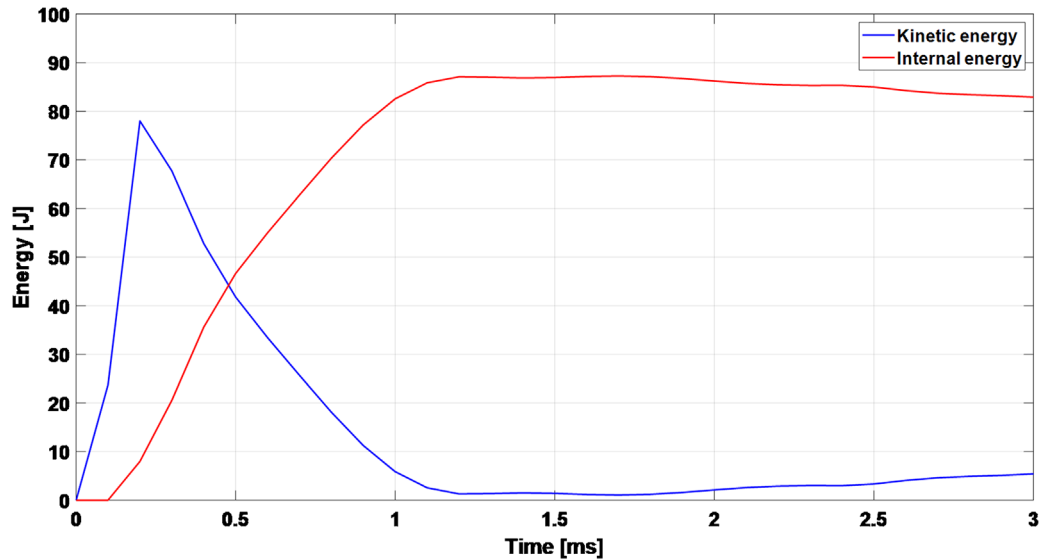


Fig. 11. Kinetic energy of the front plate and internal energy of the foam when the protective foam is added.

to crush. At 0.3 ms, the compaction wave has traveled through the complete foam thickness after which the backplate starts moving (Fig. 10a). At 1.1 ms, the backplate reaches the maximum out-of-plane displacement (Fig. 10a). Nonetheless, full densification is not observed across the foam thickness. Indeed, only the part of the foam adjacent to the front plate reached strain of approximately 42% while the densification strain is 72%.

The blast energy is uniformly absorbed through layer-by-layer compaction of the foam material, as illustrated in Figure 10. In Figure 11, the time history of kinetic energy of the front plate and absorbed energy of the foam is compared. Initially, the kinetic energy of the front plate increases as the blast load accelerates the front plate. The maximum kinetic energy is observed at 0.2 ms (Fig. 11). However, the absorbed energy of the foam steadily increases from the beginning of the process, primarily due to the brittle behavior of the mineral foam. The energy absorption occurs through core crushing, which contributes significantly to the overall dissipation of energy. The maximum energy absorption occurs at 1.1 ms, corresponding to the time when the protected configuration experiences the maximum out-of-plane displacement.

3 Conclusions

In this paper the response of a brittle mineral foam based sacrificial cladding to an air-blast loading is studied numerically. The model of the foam is developed based on an analytical relationship between the compressive strength, strain and strain-rate. Two finite element approaches are used: a Lagrangian formulation and the meshless approach using SPH. The Lagrangian model of the foam underestimates the maximum out-of-plane displacement with a mean relative error of 40%. The SPH approach predicts the experimental out-of-plane

displacement with a relative error compared to the experimental outcome ranging from 3% to 7%. The foam is found to absorb the blast energy layer by layer. Full densification is not observed across the foam thickness. The maximum strain achieved is approximately 40%, while the densification strain is 72%. Dynamic characterization of the foam should be conducted to further validate the numerical model.

Acknowledgements. The authors are grateful to the staff of the Laboratory of Propellants, Explosives and Blast Engineering (PEBE) department of the Royal Military Academy (RMA) in Brussels for their support and assistance in performing the different steps of the experimental work.

Conflicts of interest

The authors declare no conflict of interest.

Funding

The Article Processing Charges for this article are taken in charge by the French Association of Mechanics (AFM).

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Cite this article as: A. Aminou, B. Belkassam, O. Atoui, L. Pyl, D. Lecompte, Numerical modeling of brittle mineral foam in a sacrificial cladding under blast loading, *Mechanics & Industry* **24**, 27 (2023)