Simulation of Shock Wave Mitigation in Granular Materials by Pressure and Impulse Characterization

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ABSTRACT

The detonation of an explosive charge has two major effects, blast wave generation and fragmentation. New technologies of energy dissipation, based on granular materials, seem to have good shock attenuation capabilities. Plastic deformation, brittle fracture and comminution are different mechanisms of dissipation which can take place in granular media, allowing blast energy absorption and reduction of dynamic solicitation applied on structures.

Dynamic solicitation of structures is determined by the reflected pressure in a quasi-static loading case or by the reflected impulse in an impulsive loading case. Blast pressure and impulse damping represent in a macroscopic way the effects of energy dissipation mechanisms appearing in granular materials. Material efficiency can be determined by the study of the attenuation of these two parameters.

Vermiculite, a porous crushable material and CRUSHMAT®, a ceramic granular material made of alumina have been tested. Blast impulse amplification has been observed with thin layers of vermiculite while with CRUSHMAT® only attenuation has been observed. Efficiency stagnation has also been noticed for thick layers of CRUSHMAT® in which pressure and impulse, after being passed through the sample's upper part, seem to be too low for further attenuation in the lower part of the layer.

LS-DYNA has been used to simulate the experimental setup in which reflected pressure and impulse measurements have been realized on the different samples. The simulation model has been developed for a better understanding of pressure and impulse decrease, dissipation mechanisms and macroscopic behaviour of granular materials when they are subjected to blast. The CRUSHMAT® stress-strain curve has been optimized with LS-OPT trying to allow a better correlation between simulations and experimental observations.

1. Introduction

Since there is an increasing interest in the energy dissipation capabilities of granular materials in several civil domains and mostly in the military area of ballistic protections, many methodologies have been developed to study their efficiency. As blast reflected pressure and impulse on a structure are two important parameters for loading characterization, their attenuation due to the presence of granular materials between the explosive charge and the considered structure seems to be a good methodology to evaluate their capabilities.

The experimental setup presented in figure 1 is used to evaluate the dissipative characteristics of different granular materials. A 20 g C4 explosive charge is placed 40 cm above the centre of an aluminium plate (1060 x 200 x 4 mm) fixed at its edges. A blast pencil at 40 cm of this charge allows the measurement of incident pressure and impulse. A deflection sensor (Linear Variable Differential Transformer) and an accelerometer fixed at the centre of the plate provide deflection and acceleration measurements. A pressure sensor has been placed at the centre of the plate, facing the charge to provide values of blast reflected pressure and impulse.

Samples of different granular materials have been placed at the centre of the plate (granulates are packed in a thin geotextile and polyethylene plastic to prevent the spread of material). Sample dimensions are 250 x 200 x H mm, where the sample thickness H can take values from 1 cm to 9 cm. Reference tests are also conducted with the plate alone (H = 0 cm).

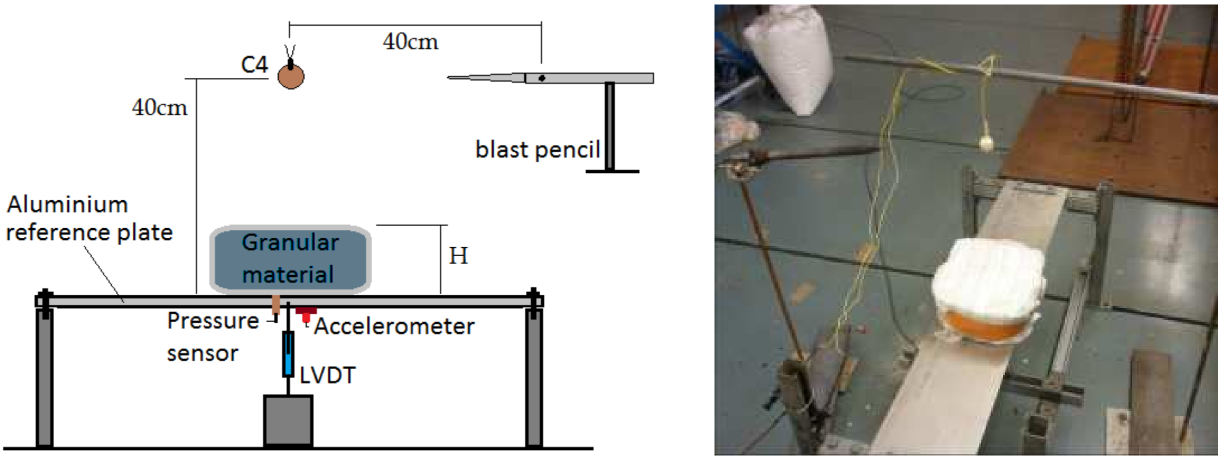


Figure 1 – Experimental setup

As deflection and acceleration measurements had a large correlation with sample mass and did not allow any conclusion about the material's efficiency, only reflected pressure and impulse were studied. This paper compares numerical simulations with experimental results and tries to understand the deformation mechanisms leading to dissipative characteristics.

2. Blast Loading and Material Parameters

LS-DYNA was used to simulate the experimental setup with the very simple model presented in figure 2.

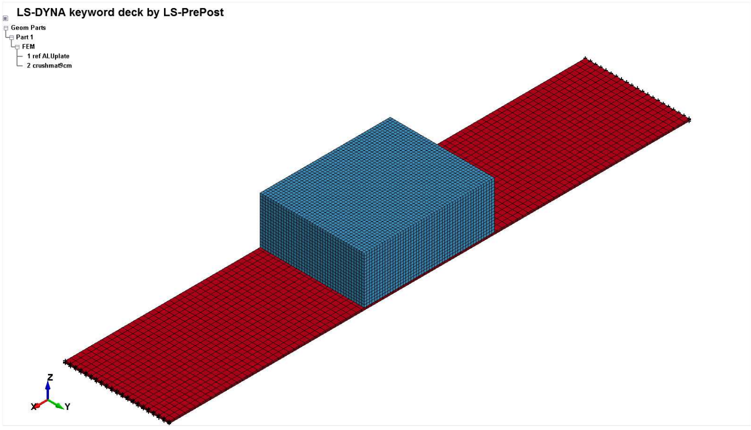


Figure 2 – Discretization of the experimental model with a 9 cm thick sample

2.1 Blast Loading Function

ConWep's data have been introduced to simulate incident blast pressure and impulse on the plate. The *LOAD_BLAST function with a 25.6 g TNT (corresponding to a 20 g C4-charge) at a stand-off distance of 40 cm is used to directly apply the reflected pressure profile on the plate and granular material, allowing a large time benefit in comparison to full ALE models. Although it is not a problem in this case, the ConWep methodology cannot be used for modelling geometries with shadowing (obstacles between charge and structure), soil reflections or side effects. Moreover, the assumption is made that plate and granular material are considered as rigid bodies at the time of arrival of the blast wave. Experimental results (Figure 3) show that the displacement of the plate during the positive phase of the loading can be neglected. Although the density of the granular material is low, it is still much higher than the air density. The granular material can thus be considered as rigid in a first approximation.

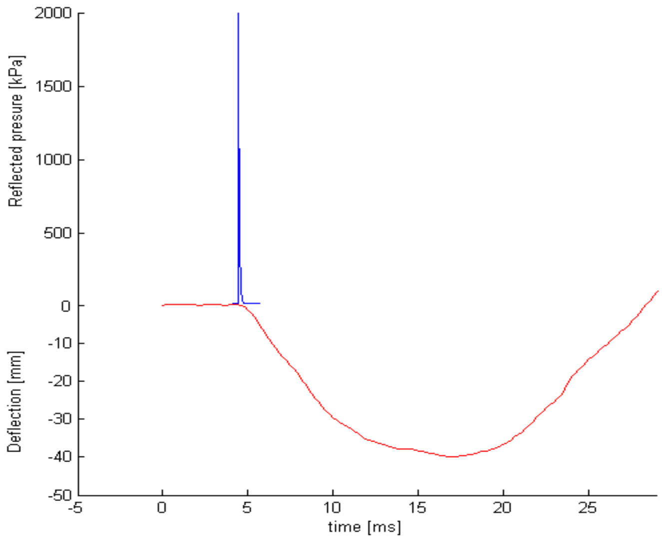


Figure 3 – Positive phase duration (blue) vs. reference plate displacement (red)

2.2 Parameters

2.2.1 Material parameters

Plate cell dimensions are 1x1x0.2 cm while granular material is discretized with 0.5x0.5x0.5 cm cells. *MAT_ELASTIC (material 001) is used as model for the aluminium plate and *MAT_CRUSHABLE_FOAM (material 63) is used for granular material modelling. Data for CRUSHMAT® material come from Niras-Demex [2] and are presented in table 1, as well as data for the reference plate and vermiculite.

Material	LS-DYNA cards (Units = m, kg, s)					
Plate	*MAT_ELASTIC					
	RO	E	PR			
	2770	7.1E+10	0.33			
CRUSHMAT	*MAT_CRUSHABLE_FOAM [2]					
	RO	E	PR	LCID	TSC	DAMP
	600	6.897E+10	0.28	3	2.41E+6	0.2
Vermiculite	*MAT_CRUSHABLE_FOAM					
	RO	E	PR	LCID	TSC	DAMP
	140	0	0/0.28	4	0	0.2

Table 1 – Material parameters

Vermiculite's Poisson ratio (PR) is set to 0 and results are compared to results obtained with a PR of 0.28. Tensile stress cut-off (TSC) and Young modulus (E) values are not known and are set to 0. E and TSC are used for elastic unloading, following Young modulus slope and stopping when tensile stress cut-off value is reached. It has to be noticed that simulations with different values of E have been run but nearly no difference appears in the results. When a high value of TSC is set, parasite oscillations of contact force between reference plate and vermiculite are observed, probably because of the reference plate's eigenmodes. This is due to the reloading which has the same elastic behaviour as for the previous unloading (reloading follows E slope).

The LCID parameter refers to a unique load curve necessary for the *MAT_CRUSHABLE_FOAM material model and is introduced with the *DEFINE_CURVE function. Couples of points defining stress-strain curves are obtained from confined static uniaxial compression tests. Stress-strain curves of CRUSHMAT [2] and vermiculite are presented in figure 4. *DEFINE_CURVE function also contains 4 other parameters which allow stress-strain curve modification by editing scale factors and offsets of abscissa or ordinate values. These factors are of great interest as design variables for further stress-strain curve optimization with LS-OPT.

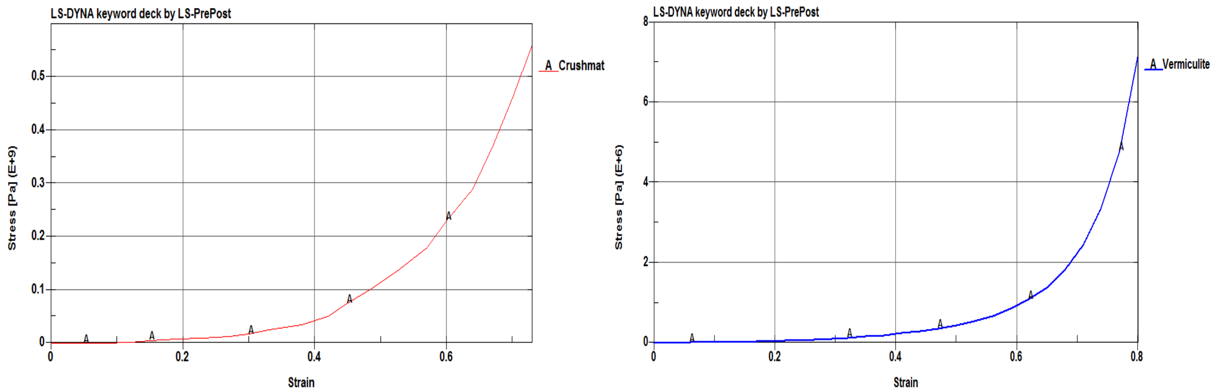


Figure 4 – CRUSHMAT® and vermiculite static stress-strain curves

2.2.2 Contacts and boundary conditions

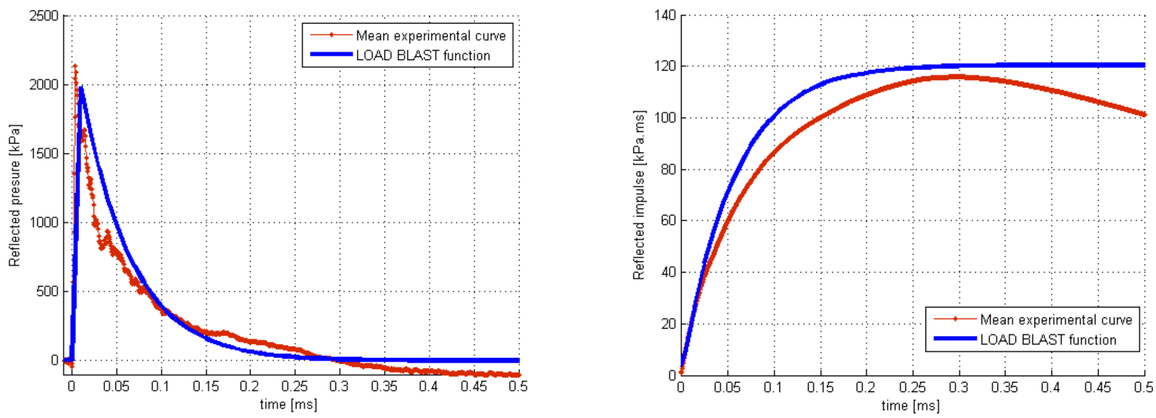
Contact between plate and granular material has been modelled with the *CONTACT_TIED_SURFACE_TO_SURFACE_OFFSET algorithm allowing a contact between a rigid body and deformable materials in which the plate is defined as master and the granular material as slave part [3].

Boundary conditions are set to constrain the two edges of reference plate in all degrees of freedom.

3. Results: Simulation vs. Experiments

3.1 Blast function

*LOAD_BLAST function is in good agreement with experimental results [4]. Red lines on figure 5 represent mean experimental curves of pressure and impulse while blue lines represent the reflected pressure and impulse profiles applied at the reference plate centre.



(a) (b)

Figure 5 – Reference reflected (a) pressure and (b) impulse

3.2 Mesh sensitivity

The mesh of the granular material was initially decreased to 0.25 cm cubic cells. Maximal reflected pressure values for 1 cm and 3 cm thick samples respectively decreased from 940 kPa to 830 kPa and from 365 kPa to 220 kPa while maximal reflected impulse only decreased by less than 1 kPa.ms for both samples.

Simulations with the 4 cm and 9 cm thick samples with 0.25 cm cubic cells did not work and returned error message concerning the charge range which is too close for the application of *LOAD_BLAST function. Decreasing mesh size to 0.125 cm cubic cells for 1 cm and 3 cm samples gave also simulation error (negative cell volume and complex sound speed in cells). The results presented in this paper are therefore computed with a 0.5 cm cubic cells mesh.

3.3 Crushmat and vermiculite

Blast reflected pressure and impulse are measured at the center of the aluminium reference plate. Figures 6 and 7 present pressure and impulse values in function of granular material thickness. The dashed lines are minimum and maximum experimental results obtained during blast tests [4].

Figure 6 shows results for CRUSHMAT®. The 1 cm thick sample does not correlate well with experimental data: the simulated pressure is at least two times higher than the experimental one even if a smaller mesh would be used. The rise time to reach this pressure is much smaller in the simulation (less than 0.05 ms) than the one in the experiments (about 0.2 ms). On the contrary, blast impulse for the 1 cm thick sample seems to match the measurements.
This is due to a shorter duration of the positive phase of the pressure profile which compensates the higher maximal pressure. Results for thicker samples present a better correlation between simulations and experiments since both reflected pressure and reflected impulse fall between the curves of the experimental domain.

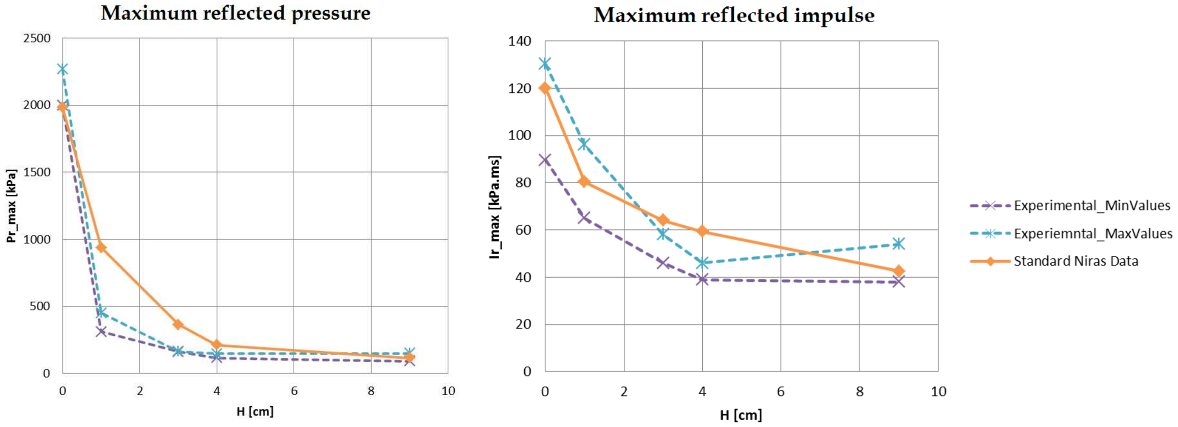


Figure 6 – CRUSHMAT®'s reflected pressure and impulse

Figure 7 shows results for vermiculite with Poisson ratios of 0 and 0.28. Almost no difference is observed between these two cases, meaning that confinenent has no big influence on vermiculite's behaviour. As for CRUSHMAT®, the vermiculite 1 cm thick sample shows a too high maximal pressure compared to experiments while thicker samples show a better correlation. Maximal reflected impulse seems a bit underestimated since simulation results take values of about 20 kPa.ms below the minimum experimental curve. However, the trend is well visible, as well as for CRUSHMAT®.

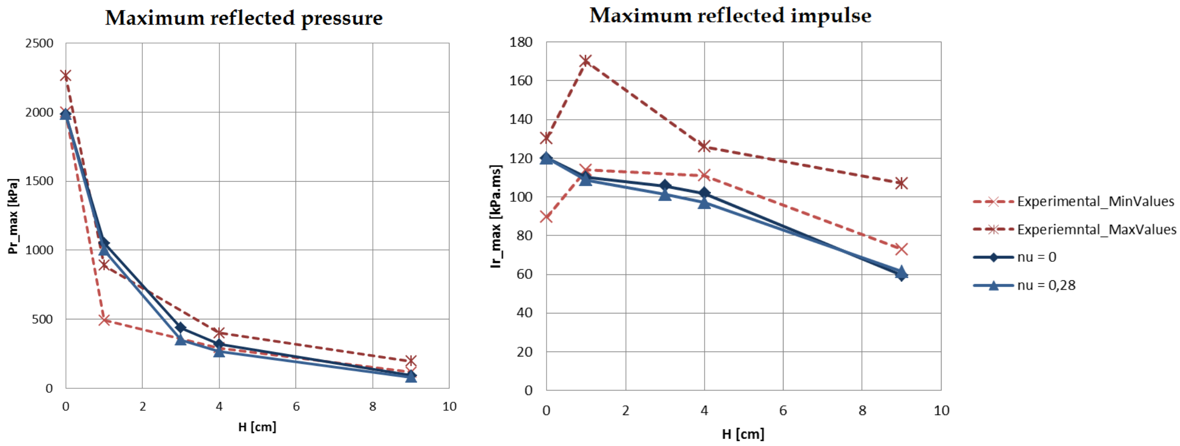


Figure 7 – Vermiculite's reflected pressure and impulse

4. Discussion

For the pressure profile of the 1 cm thick sample of CRUSHMAT® there is not a good correlation between simulations and experiments, which is probably due to a too low pressure level and the small domain used in the stress-strain curve. Indeed, the maximum experimental pressure is about 4 MPa (for the 9 cm thick sample) while a pressure of about 100 MPa is necessary to reach a strain of 0.5 which means that a 20 g C4 charge with a stand-off distance of 40 cm does not allow a high level of deformation. Moreover, as the stress and strain levels stay low, only the beginning of the stress-strain curve is used in the simulation and imprecision in this domain is high, which can explain deviation between experimental and simulated pressure profiles. Underestimation of the reflected impulse in the case of vermiculite is due to a too short positive phase duration, which decreases more vertically whatever the value given to the Young modulus acting on unloading behaviour.

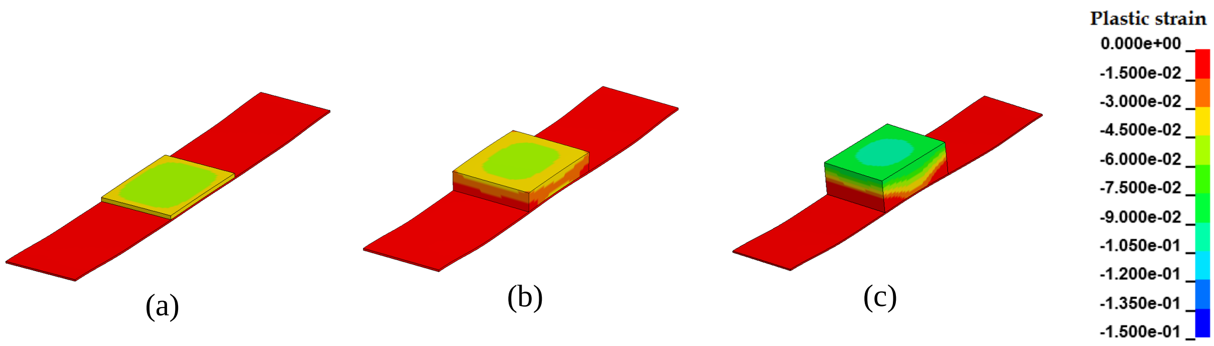


Figure 8 – Plastic strain of CRUSHMAT® at 1.5 ms for (a) 1 cm, (b) 4 cm, and (c) 9 cm

Figures 8 and 9 show plastic strain at 1.5 ms respectively for CRUSHMAT® and for vermiculite with Poisson ratio equal to zero. Samples with different thicknesses are presented. The time of 1.5 ms has been chosen to be much higher than the pressure positive phase duration in a way that plastic strain is fully established at that time.

CRUSHMAT® behaviour is qualitatively represented by the plastic deformation visible in the samples. It seems that the 1 cm thick sample is uniformly compressed up to a certain strain level while the 4 cm and 9 cm thick samples are deformed in a decreasing way across the thickness. For these samples, plastic strain near the plate is much lower than the plastic strain at the top layer. Blast energy seems to be absorbed progressively through the thickness, beginning with the first layers until the remaining energy is too low to deform the material in the lower part.

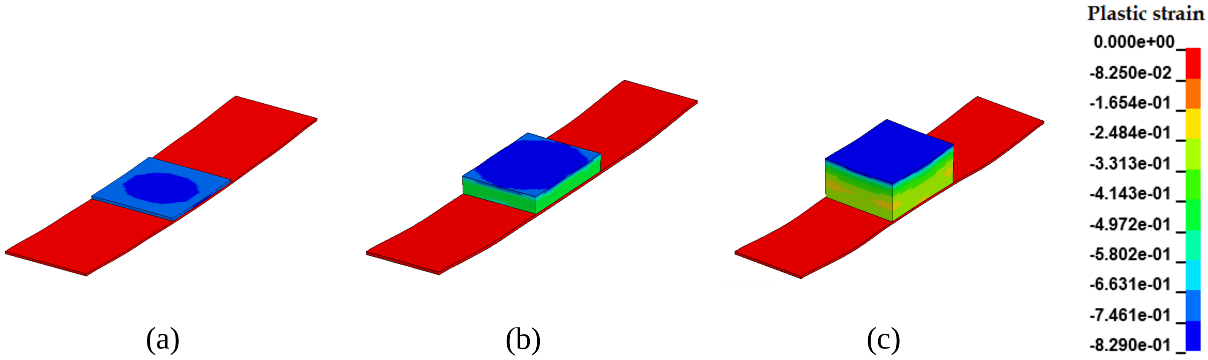


Figure 9 – Plastic strain of vermiculite at 1.5 ms for (a) 1 cm, (b) 4 cm, and (c) 9 cm

Vermiculite seems to have a very different behaviour. First, plastic deformation is higher for all samples than deformation obtained with CRUSHMAT. Secondly, the pressure in vermiculite seems not to be distributed through the entire sample's thickness. A thin layer on the top seems to be much more deformed than the intermediate and lower layers. This phenomenon is the qualitative visualization of densification of the sample's upper part. Although impulse amplification is not visible for the 1 cm thick sample with these simulations, this behaviour was highlighted during experimental tests [4].

5. Material parameters optimization: LS-OPT

5.1 Theoretical background

As simulation results of pressure and impulse do not correctly match the experimental data curves, it would be interesting to optimize model parameters. In fact, stress-strain curves of granular materials introduced in the initial model were derived from static compression tests. Assuming that blast generates dynamic effects, an improvement of stress-strain curve could improve the results. LS-OPT allows the calibration of defined material parameters by adjusting simulation results to experimental baseline tests thanks to optimization methods which minimize the mean square error (MSE) between experimental and simulated points (Figure 10).

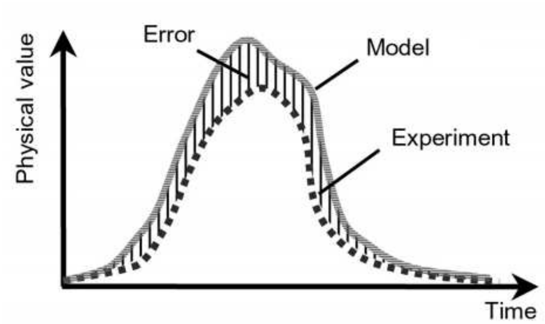


Figure 10 – Schematic difference between experimental test and simulation result [6]

Let's consider the optimization of two parameters x_1 and x_2 called *design variables*. Combinations of values for these design variables are chosen in a prescribed range allowed by the user, called *design space*. Based on the different combinations of these design variables, several simulations are run. Residual errors between experimental and simulated curves are calculated for each simulation and are used to calculate the Mean Square Error (MSE). A statistical method called Response Surface Methodology (RSM) allows an approximation to the objective function (minimizing MSE) in the multi-dimensional parameter space [5]. Evaluation of the MSE with several values of parameter x_i allows the construction of RSM. These values, i.e. points from design space, are selected with a Design of Experiments (DOE).

The response surface for 2 parameters x_1 and x_2 is presented in figure 11. Different polynomial functions can be used for interpolation between the calculated model responses. Linear approximations do not give good result for the first iterations because of a large surface response but it can be introduced in a Sequential Response Surface Methodology (SRSM) [6].

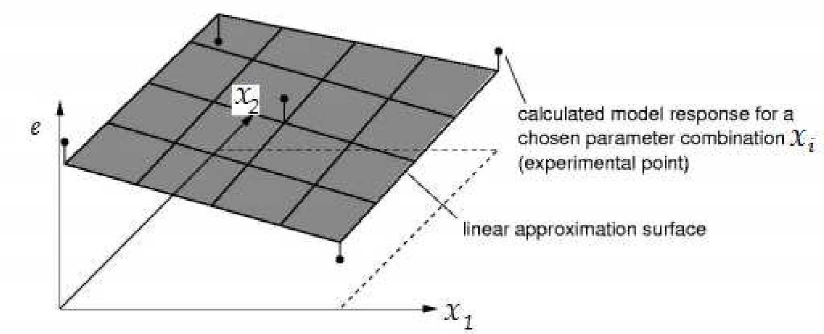


Figure 11 – Response surface based on linear interpolation [6]

Sequential Response Surface Methodology requires initial lower and upper boundaries, respectively *rL,0* and *rU,0*, which define the limits of response surface (Figure 12). When the optimum of the surface is found (an approximate optimum), a new adapted region is defined in which the same procedure is executed until reaching the required tolerance. SRSM allows a good accuracy of linear interpolations after only a few iterations [6].

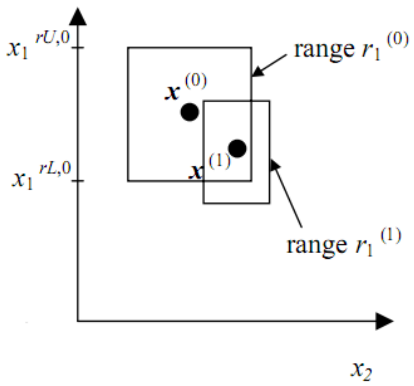


Figure 12 – Sequential Response Surface Methodology [6]

5.2 Approach

The reflected experimental pressure profile is selected as the target curve. The x-axis variable is defined as time and the y-axis variable as pressure. Material parameters first introduced in the *MAT_CRUSHABLE_FOAM material model (i.e. stress-strain curve) are optimized in order that computed response curves approach experimental curves.

CRUSHMAT®'s parameters are optimized with a *single case history-based MSE* in which parameter's optimization is based on only one sample configuration (1 cm thick sample). The DAMP parameter for this sample is set to 0.05. Validation of the improved material parameters is done by comparison between computed and experimental curves of other configurations (3 cm, 4 cm and 9 cm thick samples).

5.3 Design variables

As the initial CRUSHMAT® stress-strain curve is based on a static compression test and experimental data are results from (dynamic) blast tests, this curve has to be adapted in order to optimize the granular material computed response. The easiest way for modification is to define scale factors on abscissa and ordinate values, respectively *sfa* and *sfo*. These design variables can be defined in LS-DYNA using *PARAMETER_DEFINE cards and clicking on *PARAMETER option in *DEFINE_CURVE card. Range is established between 0.3 and 1 for *sfo* and between 1 and 10 for *sfa*.

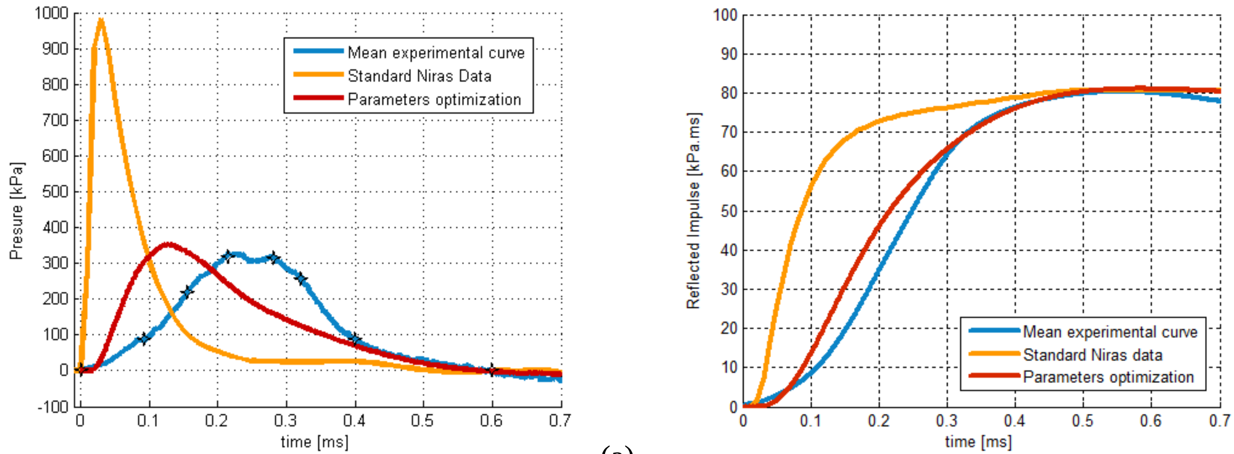
5.4 Response surface method

Linear approximation is used as polynomial interpolation and is coupled with a SRSM. D-optimal criterion is applied as DOE to find points in the design space [6].

5.5 Results and discussion

After only two iterations, LS-OPT converged to “optimum values” of *sfa* = 10 and *sfo* = 0.3. This rapid convergence is due to the fact that these values are defined as limits of design variables ranges; DOE algorithm first chose boundaries of design space so that results can be interpolated between these limits (with purpose of SRSM application). Although MSE is minimized with these values, the computed pressure curve of the 1 cm thick sample is lower than the target curve. This is due to the fact that not the entire experimental curve is entered as target curve, but only a defined number of points (represented by small black stars on figure 13(a)). The number of points located on the top of the pressure profile is too low and their weight in the optimization process by Mean Square Error method is therefore small, which means that pressure peaks are smoothed. However, increasing the amount of target points near maximal pressure did not change results. This is probably due to the incapacity of decreasing much more the MSE with other scale factor values because of the unfeasibility of reaching target points with the granted leeway, the design variables chosen and the initial stress-strain curve. A more suitable approach would be to adapt the stress-strain curve by modifying the value of each stress-strain couple instead of using scale factors. So, more appropriate values based on qualitative observation are chosen (*sfa* = 10 and *sfo* = 1) for still keeping a maximal reflected pressure around 350 kPa. It has to be mentioned that experimental curves are also subjected to imprecision, reproducibility of tests results being not perfect.

The reflected pressure and impulse of the CRUSHMAT® 1cm thick sample for these design variable values are presented in figure 13. The blue curves are the mean of the experimental curves; small black stars are points from this experimental curve which are defined as target for parameters optimization. Yellow curves are pressure and impulse curves obtained with the initial stress-strain curve from [2], while the red curves are computed curves resulting from design variables optimization with *sfa* = 10 and *sfo* = 1.



(a)

(b)

Figure 13 – (a) Reflected pressure and (b) reflected impulse for the 1 cm thick sample of CRUSHMAT®

Figure 14 presents maximum reflected pressure and impulse of computed curves using initial stress-strain data for different sample thicknesses, compared to maximum values from optimized computed curves. An improvement is clearly visible, mainly for reflected pressure.

Physically, introducing a strain scale factor of 10 means that for a same stress, granular material would deform ten times more than expected using the initial stress-strain curve. Despite relatively good optimized results, such a big difference between initial and optimized stress-strain curves can be very questionable. A possible reason could be the uncertainty in the first part of the experimental stress-strain curve.

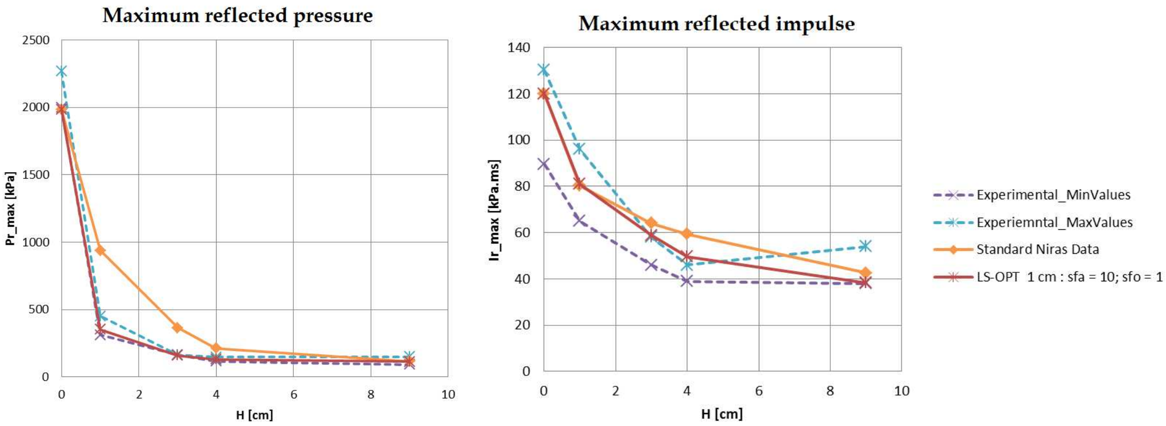


Figure 14 – CRUSHMAT®'s reflected pressure and impulse based on 1 cm-sample parameters optimization

6. Conclusion

This paper compared the behaviour of two very different granular materials under blast loading and tries to understand shock absorption behaviour with simple simulations. Although computed pressure and impulse values are not completely in good agreement with experimental results, general trends and the two different behaviours emerged. In addition to some technical problems remaining, results demonstrate the importance of very good initial data describing the materials to be modelled.

Densification could be observed for vermiculite but as impulse amplification was not visible in the simulation, it would be of great interest to study this phenomenon through MMALE simulation. In order to save time, *LOAD_BLAST_ENHANCED function can be used for the direct application of incident pressure on an ALE domain close to the granular material.

LS-OPT, a parameter optimization tool, was used to fit computed pressure curves to experimental curves with relative success. Nevertheless, two other optimization approaches with LS-OPT can be considered in further works. First, points from stress-strain curves could be individually adapted to have a better correlation with measurements, and secondly, design variables optimization could be established by a *Multi case history-based MSE* in which results from several experiments are used at the same time for curve fitting. Experimental pressure curves with 1 cm, 3 cm, 4 cm and 9 cm thick samples would be chosen to be target curves and validation of improved parameters would be done by a new experimental test with another charge or another sample configuration (e.g. big-scale test) to be compared with the corresponding LS-DYNA model simulation.

7. References

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