On the design and evaluation of light weight metal protection concepts against blast loading using LS-DYNA

A. Gakwaya*,[*] G. Toussaint*, P. Gaudreault*, K. William[**], R. Durocher[**]

Summary

The aim of this paper is to find a lightweight protection system that can replace steel based concepts used to resist mine blast effects without failure and with no excessive deformation of the passengers' cabin. The simulation of the initial steel concept and of a new replacement concept based on fully dense lightweight metals is first presented. Then, a multilayered design of sandwich type with ballistic alloys as faces and aluminium foam as core was explored. Since material models for aluminium foam being still under development, their constitutive parameters are not readily available. Hence some effort has been deployed first in order to find the appropriate foam and its structural properties. Preliminary results show that the chosen dense lightweight metals present a higher energy absorbing capacity than steel and hence could effectively replace it. However, the results obtained when studying the response of the sandwich structure do not allow us to draw similar conclusion. Further studies and material characterization are still needed.

Introduction

In the last decades, automotive and transport industry has recognised the importance of safety incorporated components as competitive marketing advantages. Moreover, requirements on carbon dioxide emissions and the desire for vehicles with economical handling put additional restrictions on the vehicle weight. But, the demand for increasingly safer vehicles poses added challenges to vehicle design when combined with the desire for low weight. To fulfil the total set of requirements, typical needed actions are thus redesigned structural elements, incorporating often new materials. Lightweight materials with high mass specific energy absorption capabilities, such as metal foams, are thus candidates for some of tomorrow's vehicle components [8].

A typical aim here is to develop lightweight structures which are enough stiff and strong but, yet, can absorb large amounts of blast/impact energy so as to avoid structural failure and excessive deformation of passengers' cabin. The blast wave, in the form of a transmitted pressure wave, can generate various levels of compressive and shear stresses

[*]Dept of mechanical engineering, Laval University, [**]DRDC-Valcartier, Canada

Proceedings of the 2004 International Conference on Computational & Experimental Engineering & Science 26-29 July, 2004, Madeira, Portugal

which can lead to critical damage of the protection system and its supporting structure. Energy absorbers are often part of the vehicle structure to protect passengers and the structure itself during impact or blasts loadings. In lightweight armoured vehicles subject to mine threats, energy absorbers must be placed on the most vulnerable regions of the frame including the cabin floor. In this study on blast loaded specimens, the material selection will be based on energy absorbing capability, allowable maximum deformation without failure, plate thickness and minimum costs. Materials available for selection include dense lightweight alloys based either on aluminum or either on titanium and metallic sandwich panel with aluminum foam core.

Our objectives will be achieved by first determining what lightweight alloys can replace steel as an efficient structural protection against mine blast and, secondly, by assessing if the introduction of aluminum foam core in a given sandwich construct made of selected dense aluminum alloy can replace a standard metallic plate as an efficient protection system. Since experimental tests in impact or blast behavior may be cost prohibitive, numerical tests are first considered in this preliminary study in order to select the most promising scenarios. Hence, trial and errors tests will be avoided and the final real time physical testing will be designed so as to minimize the experimental costs.

Initial protection concepts

Figure 1 shows the situation to be simulated and represents an experimental setup used to evaluate the response of vehicle protection system against an underneath mine blast. Existing protection concepts are made of steel and the objective is to find a novel lightweight material that is most efficient for a given blast loading, in energy absorption, in allowable maximum displacement and resistance to material failure. Based on previous modeling practice [9], a proof of concepts can be achieved by considering that the original steel plate is clamped along its edges and dynamically loaded by a mine blast on its lower surface. The actual plate has dimensions 6' x 6' and 1.25'' thick and symmetric conditions are assumed to prevail so that a quarter plate has been discretized using shell elements. An elastoplastic material allowing for isotropic and kinematic hardening, i.e. the LS-DYNA MAT_PLASTIC_KINEMATIC model was used. The standard required material parameters for dense metal analysis are volumic density (g/mm^3), Young's modulus E in GPa, elastic limit in (σ_y in MPa), Poisson's ratio υ and tangent modulus Etan (MPa). For modelling using LSDYNA, the following simplifying assumptions were introduced: (i) elastoplastic material models are used without failure limit; (ii) properties are assumed to correspond to their quasistatic values and thus independent of loading velocity (Normally in such a study one would expect strain rate dependent response); (iii) temperature effects are neglected during impact; (iv) the initial loading velocity is inversely proportional to the plate thickness (as computed by the impulsive loading model). Modeling the mine blast load was performed by generating initial velocities with an impulsive loading model (for shell elements)or by using an equivalent pressure loading from the LS-DYNA LOAD_BLAST function i.e. a pressure function (over time and space) applied over the plate, with values calibrated from the impulsive model. In order to observe some spring back response and at the same time reduce the simulation time and computer memory required for real time simulation and visualisation, a time step between 0.1ms and 1ms was seen to give interestingly enough results.

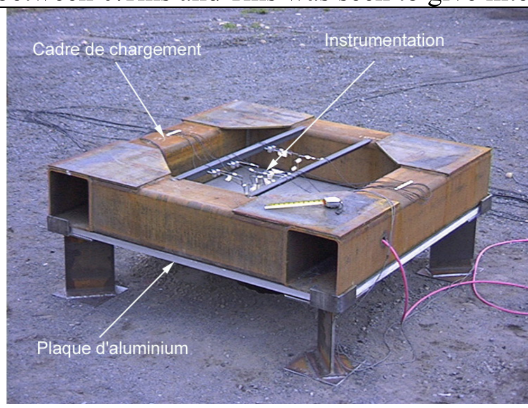

Figure 1. Experimental set up for evaluation of structural plate response to blast loading

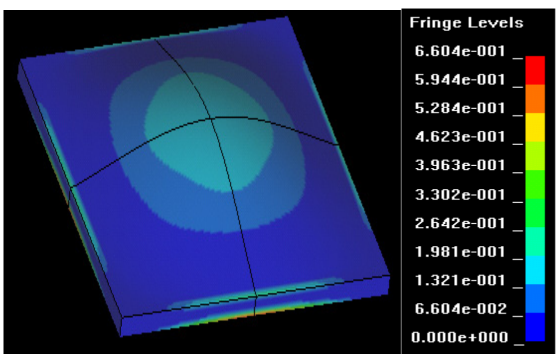

Figure 2.Deformed shape of an Al 5083-H131 plate with 50.8mm thickness.

The typical results obtained for dense lightweight material are shown in figure 2. Several alloys have been tested and some of the most promising are presented in [9]. Since the criteria used for assessing if a material is acceptable or not are often contradictory, the designer has to take himself a decision based on other criteria like manufacturing cost and product availability. Energy absorption levels computed from the generated stress-strain curves for various considered alloys showed that although titanium alloy is the best energy absorbing metal, it is however expensive and less ductile than the closest aluminum alloys. Hence aluminum alloys will be preferred to titanium alloys.

Development of a sandwich plate model

Combinations of different materials in form of a composite structure are commonly used in many engineering applications. A major benefit of composites, compared to standard metallic materials, is the high strength to weight ratio which results in low structural weight. Recently, low cost aluminium foams have been produced for a wide range of potential applications such as the cores of sandwich panels and various automotive parts. Foamed aluminum alloys are ultra-light solids, which absorb considerable energy by plastic dissipation in compression. Their cellular microstructure endows them with the ability to undergo large deformation at nearly constant nominal stress. It is expected that they will find application in absorbing impacts and shocks (e.g.

crash barriers and blast mitigators). Such use of aluminum foams requires however prior knowledge of the effect of impact velocity and strain rate on their compressive behavior. Two LS-DYNA metal foam materials were tested: Material Model #126 for aluminum honeycomb crushable foam and Material Model #154 for crushable metal foam plasticity. The first model #126 is mainly dedicated to honeycomb and foamed structures. A decoupled non linear elastoplastic behavior can be defined for normal and shear stresses. This model is used with solid elements only and it is possible to simulate the deformation of honeycomb crushable foam with anisotropic behavior. The problem with this model is that the material behavior must be defined separately for normal and shear stress. The second model #154 is mainly dedicated to aluminum foam used as filler so as to enhance energy absorbing capability of extrusions. Its successful implementation for metallic foams requires the development of design methods based on reliable constitutive laws. A phenomenological model proposed in [6] was taken as the basic model for the plastic deformational behavior of aluminum foams. The yield function ϕ in eqn. 1, depends on the two stress invariants σ_m and σ_e and the shape of the flow surface remains the same during plastic evolution.

$$\phi = \left(1 \Big/ \left[1 + (\alpha/3)^2\right] \right)\left(\sigma_e^2 + \alpha^2 \sigma_m^2\right) - \sigma_y^2 \le 0 \quad \text{and} \quad \sigma_e = \sqrt{\frac{2}{3}\sigma^{dev} : \sigma^{dev}} \qquad (1)$$

where σ_y is the flow stress in tension or compression, σ_m is the mean stress and the parameter α defines the shape of the yield surface and is the ratio of the shear to hydrostatic yield strengths. The hardening behaviour is expressed by the evolution the yield stress as:

$$\sigma_y = \sigma_p + \gamma * \frac{\varepsilon}{\varepsilon_D} - \alpha_2 * \ln\left\{1 - \left(\frac{\varepsilon}{\varepsilon_D}\right)^{\beta}\right\} \quad \text{with} \qquad \varepsilon_D = -\left(\frac{9+\alpha^2}{3*\alpha^2}\right) * \ln\left(\frac{\rho_f}{\rho_{f0}}\right) \qquad (2)$$

where ε_d is to the densification strain, ρ_f is the density of the foam and ρ_{f0} is the density of the compressed material. σ_P, γ, α_2, β are the material parameters to be determined from compression tests. Fig. 3 shows a typical nominal stress versus nominal strain curve for quasi-static (strain rate=$10^{-3}s^{-1}$) compression of typical Al foam, of relative density 0.15. The curve presents four features: (1) an initial linear elastic region; (2) an yield point; (3) a plateau region where the stress increases slowly as the cells deform plastically, and (4) a region of rapidly increasing load as the cell edges progressively touch each other. Recent high strain rate compressive behavior of cellular aluminum alloys investigated using the split Hopkinson pressure bar and direct impact tests show that the dynamic behavior of these foams is very similar to their quasi-static behavior and that the plateau stress is almost insensitive to strain rate, for $\dot{\varepsilon}$ up to 5000 s^{-1} [2]. The experimental compression stress/strain curve of the used aluminium foam was obtained from Cymat [9] and a curve fitting process provided the following set of material parameters: σ_p=2.994 MPa, ε_D=2.14, γ=9.83, α_2=47.80, β=3.61. Figure 4 compares the experimental and computed values using the adopted model. In LS-DYNA, the material model

*MAT_DESHPANDE_FLECK_FOAM will thus be defined as: Line 1: 2, 0.000400, 396.88, 0.0, 2.12, 5.08999 and Line 2: 2.13, 43.89999, 3.04000, 3.73960, 1.0.

The next step is to simulate the sandwich behaviour under blast loading. The tested sandwich structure is illustrated in figure 5 and comprises 4 layers (bottom to top): layer 1: ballistic aluminium plate 5083-H131, layer 2: aluminum foam of 400 kg/m^3, layer 3: aluminium plate 5083-H131 and layer 4: silicon foam HT-820. Several sandwich plate models classified according to their layers' thickness have been tested. Solid elements were used in each layer and the mine blast loading was generated using the LS-DYNA LOAD_BLAST facility calibrated with the impulse model.

Results and discussion

The first results obtained and shown in table 1 are surprisingly better than expected from experimental observation. This seems to be due to numerical problems (coarse mesh, negative volumes, material parameters,…) with the new constitutive model for which mass scaling was used so as to overcome convergence problems. However this had the effect of artificially increasing the mass density of the foam thus making the foam heavier than it is in reality and thus leading to the surprisingly apparent good results. A better approach to mass scaling would have been the increase of the elastic Young's modulus of the material models. This doesn't change much the response of the material because of negligible elastic contribution compared to the plastic contribution to the total deformation of the material. This might give more realistic results as shown in [9]. Hence, it is not yet possible to conclude that

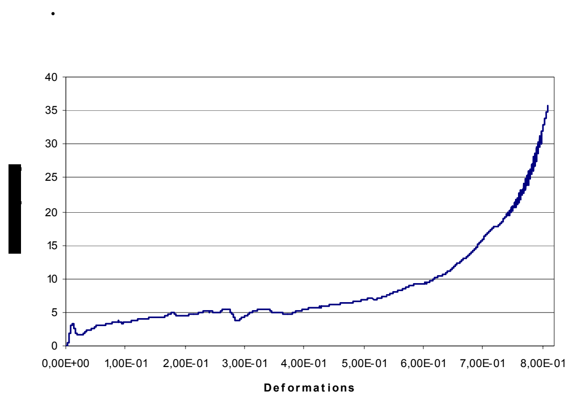

Figure 3 Typical experimental stress-strain curve for 15% Al foam (ref. CYMAT)

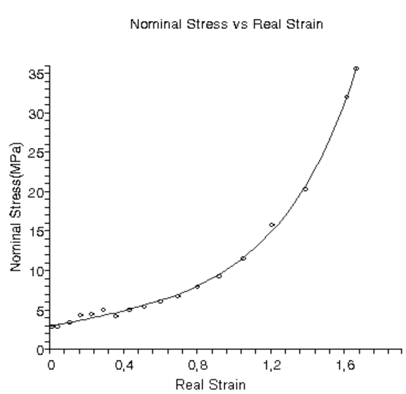

Figure 4: Nominal stress versus real strain obtained from model compared with experimental points.

the sandwich material has better performance than a plate of dense aluminium of same surface density. Hence, the loading rates used for the foam do not offer the desired performance as compared to fully dense aluminium plate. More research is still needed in order to find better foam and to rebuild a more complete model of the plate with a refined mesh. Also, experimental tests should be performed with different sandwich materials in order to validate the numerical results.

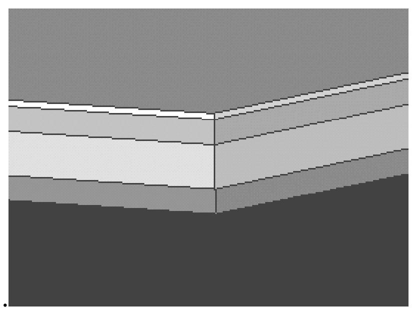

Figure 5: A four layers sandwich material (with silicon top layer)

	Displacement:layer 3	
Material	#126	#154
Model 1	80mm	81mm
Model 2	97mm	106mm
Model 3	-	-
Model 4	104mm	108mm
Model 5	119mm	132mm
Model 6	72mm	74mm

Table 1: Summary of the results obtained.

References

1. Markaki, A.E. and Clyne, T.W. (2000): "Characterization of Impact Response of Metallic Foam/Ceramic Laminates", *Mat. Science and Technology*, Vol. 16, pp. 785-791.
2. Deshpande V.S., Fleck N.A.: (2000) “High strain rate compressive behaviour of aluminium alloy foams”, *Int’l Journal of Impact Engineering, Vol. 24, pp. 277-298*
3. Chen, C., Fleck, N.A., Lu, T. J. (2001): "The mode I crack growth resistance of metallic foams", *Journal of the Mechanics and Physics of Solids 49*, pp. 231-259.
4. Miller, E., (2000): "A continuum plasticity model for the constitutive and indentation behaviour of foamed metals", *Int’l Journal of Mechanical Sciences 42, pp.* 729-754.
5. LS-DYNA ver.970 keywords and user’s manuals, www.ls-dyna.com
6. Deshpande V.S., Fleck N.A. (2000): “Isotropic constitutive models for metallic foams”, *Journal of the Mechanics and Physics of Solids, vol.48 1253-1283*.
7. Sun D.Z., Andrieux F. , Haberling C. (2003), “Characterization and simulation of mechanical behaviour of aluminium foams”, *Cellular Metals and Metal Foaming Technology.* . MIT-Verlag
8. Banhart , J. (2001), “ Manufacture, characterization and application of cellular metals and metal foams”, *in Progress in Materials Science vol.46, pp 559–632*.
9. Gaudreault, P. (2004), “Simulation statique et dynamique par la méthode des éléments finis en vue d’optimiser la performance d’un concept de protection des occupants de VBL contre les mines à effets de souffle antivéhicules », mémoire de maîtrise, Dept génie mécanique, Université Laval 2004.