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On the ballistic perforation resistance of a sandwich structure with aluminium skins and aluminium foam core

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ABSTRACT

Sandwich structures have proven to be excellent energy absorbents and are found in various protective solutions. In this study, an inhomogeneous aluminium foam was used as core material in a sandwich panel with skins of thin aluminium plates. Ballistic impact tests were conducted in a gas gun using spherical projectiles to reveal the ballistic response of the sandwich panel, and the results were compared with data from impact tests on the core material only. Numerical models, calibrated based on material tests and X-ray Micro Computed Tomography (XRMCT) data, of the ballistic impact tests were established in a non-linear finite element solver. The numerical model was found able to reproduce the complex response of the sandwich panel.

1. Introduction

Due to their many positive characteristics regarding energy absorption, aluminium foams find their use in a number of engineering applications such as core material in sandwich structures [1], sacrificial claddings for blast mitigation [2], and filler material in crash boxes [3]. However, the properties of such foams depend directly on those of the solid materials from which they are made, in addition to their relative density, cell topology, size, and shape, and the often highly inhomogeneous pore and density distribution [4]. Consequently, it has proven difficult to numerically optimise and control the behaviour of such foams under extreme loading conditions. Several authors have therefore looked to the micromechanical modelling of foams [5], but such models are in general too time consuming for large scale simulations. An alternative is to use X-ray tomography to disclose information about the microstructure. Brekken et al. [6] used X-ray micro computed tomography (XRMCT) to map the porous morphology and density variation of a highly inhomogeneous aluminium foam. The data was used to calibrate a crushable foam constitutive model intended for large scale impact simulations. Here, the same aluminium foam as in [6] was used as core material in a sandwich panel. The panel was made by adding thin aluminium plates as skins on each side of the foam core. Ballistic impact tests on the sandwich panel were conducted using a rigid sphere as a projectile, and the ballistic limit velocity of the sandwich panel was determined. Numerical models of the ballistic impact tests were finally established, and the constitutive models were calibrated based on material tests and XRMCT data. It was found that the numerical model was able to reproduce the complex response of the sandwich panels during the perforation process.

2. Sandwich panel

The sandwich panel applied in this study had in-plane dimensions of 150 mm × 150 mm and was composed of two materials: 0.8 mm thick plates in aluminium alloy AA1050-H14 as the skins, and a 50 mm thick closed-cell aluminium foam as the core. No adhesive was used between the skins and the core to simplify the numerical modelling.

The plates of alloy AA1050-H14 were produced by Hydro Aluminium and consist of 99.5% pure aluminium. Uniaxial tensile tests were carried out on dog-bone specimens cut in three different directions (0°, 45°, 90°) with respect to the rolling direction of the plate. Engineering stress–strain curves from the quasi-static uniaxial tensile tests can be found in [7], where it was found that the alloy is somewhat anisotropic in both flow stress and failure strain.

The aluminium foam was produced by Havel metal foam using the powder compaction method. Quasi-static uniaxial compression tests

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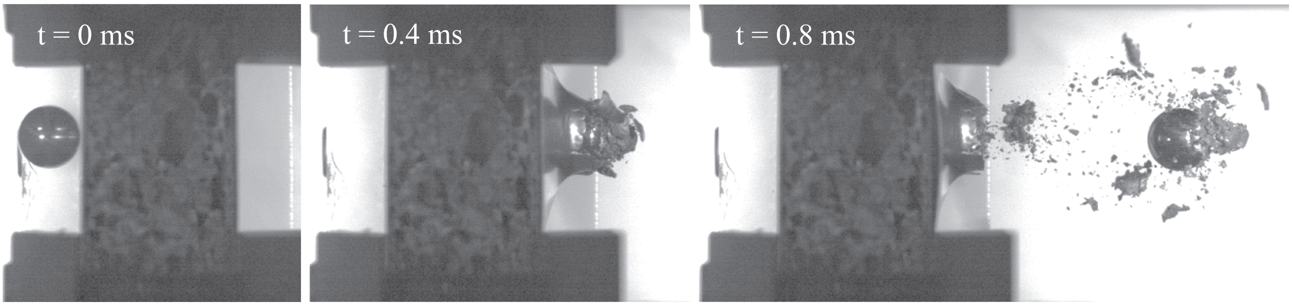

Fig. 1. Time-lapse of the perforation process from one of the tests (v_i = 208.2 m/s, v_r = 159.3 m/s).

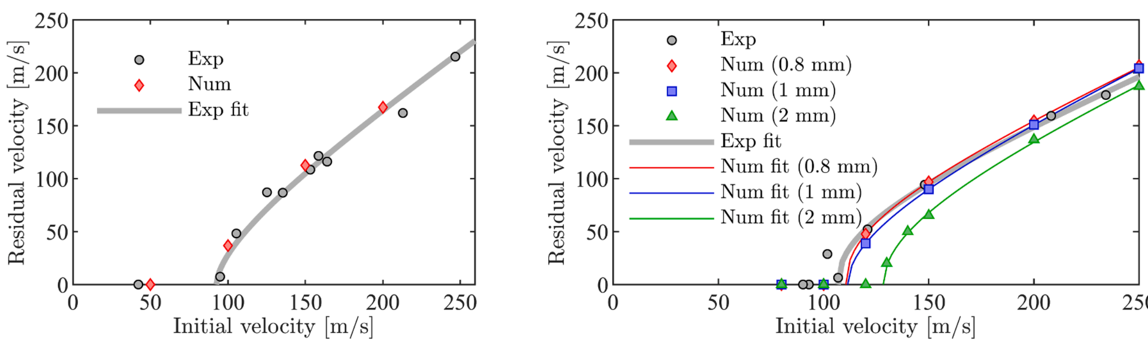

Fig. 2. Ballistic limit curve and experimental data points from impact tests on (left) the aluminium foam core only [6] and (right) the sandwich panel. Numerical results from Section 4 are also included for comparison.

were performed in an Instron universal testing machine [6]. Due to the highly inhomogeneous pore distribution of the applied foam, 20 cubic specimens with edge lengths of 50 mm were cut from the as-received plates. Prior to testing, each specimen was measured and weighed, and the overall density was found to range between 351 kg/m^3 and 633 kg/m^3 with an average of 491 kg/m^3. This gave a relative density of the foam between 0.13 and 0.23. During testing, the specimens were compressed between two rigid plates facing the external surfaces in the thickness direction. True stress–strain curves from the tests can be found in [6]. It was concluded that the stress–strain response heavily depends on the density of the sample. In addition, some of the samples were scanned prior to testing using XRMCT to study and characterise the topology and morphology of the material. The raw image stack was post-processed using the technique described in [8] to reveal the inherent density variation of the foam. Examples of the density variation in some specimens are shown in [6]. The relative density of the specimens was constant and roughly 0.2 in the in-plane directions, while significant variation occurred in the thickness direction with a local minimum of around 0.1 in the centre of the specimens that increased to above 0.5 towards the external surfaces.

3. Ballistic impact tests

The ballistic impact tests were performed in a compressed gas gun facility documented by Børvik et al. [9]. Rigid steel spheres with a diameter of 20 mm and a mass of 32.6 g were used as projectiles and launched at impact velocities between 80 and 250 m/s. The 150 mm × 150 mm × 51.6 mm thick targets were clamped between two rigid plates with an overlap of 25 mm on each boundary. During testing, a Phantom TMX 7510 high-speed camera with a recording rate of 50,000 fps was used to provide images of the perforation process (see Fig. 1 for one example). The images were also used to measure the impact (v_i) and the residual (v_r) velocities of the projectile. From these measurements, the ballistic limit (v_bl) velocity of the sandwich panel was estimated using the Recht-Ipson model [9]. Based on a best fit to the experimental data, v_bl was estimated to be 106.9 m/s. The ballistic results are shown in Fig. 2 (right), where they can be compared to the experimental results from the ballistic impact tests [6] on the foam core only in Fig. 2 (left). As seen, by adding 0.8 mm thick skins in low-strength aluminium on each side of the foam core increased the ballistic limit by 16%.

4. Numerical simulations

Numerical simulations of the ballistic impact tests were carried out in LS-DYNA. The aluminium skins were assumed isotropic and modelled using the modified Johnson-Cook model (*MAT_107), while the foam core was modelled using the Deshpande-Fleck model (*MAT_154). The modified Johnson-Cook model (with Voce hardening and Cockcroft-Latham fracture) was calibrated based on inverse modelling of the material tests using the numerical optimisation tool LS-OPT. The parameters are given in Table 1. To model the highly inhomogeneous foam core, the central impact area measuring 50 mm × 50 mm × 50 mm was replaced by 50 layers through the thickness with dimensions 50 mm × 50 mm × 1 mm (Fig. 3 (left)). This made it possible to distribute the density-dependent material parameters based on the XRMCT data within this zone. Beyond the central impact zone, the foam was modelled as homogeneous with the average density measured with XRMCT. For a detailed description of the numerical model and

Table 1
Material parameters for aluminium alloy AA1050-H14.

E[GPa]	ν[-]	ρ[kg/m^3]	σ_0[MPa]	Q_1[MPa]	C_1[-]	Q_2[MPa]	C_2[-]	$\dot{p}_0$[s^{-1}]	c_MJC[-]	W_c[MPa]
70.0	0.30	2700	80.0	25.7	1000.0	7.6	21.4	5×10^{-4}	0.014	50.8

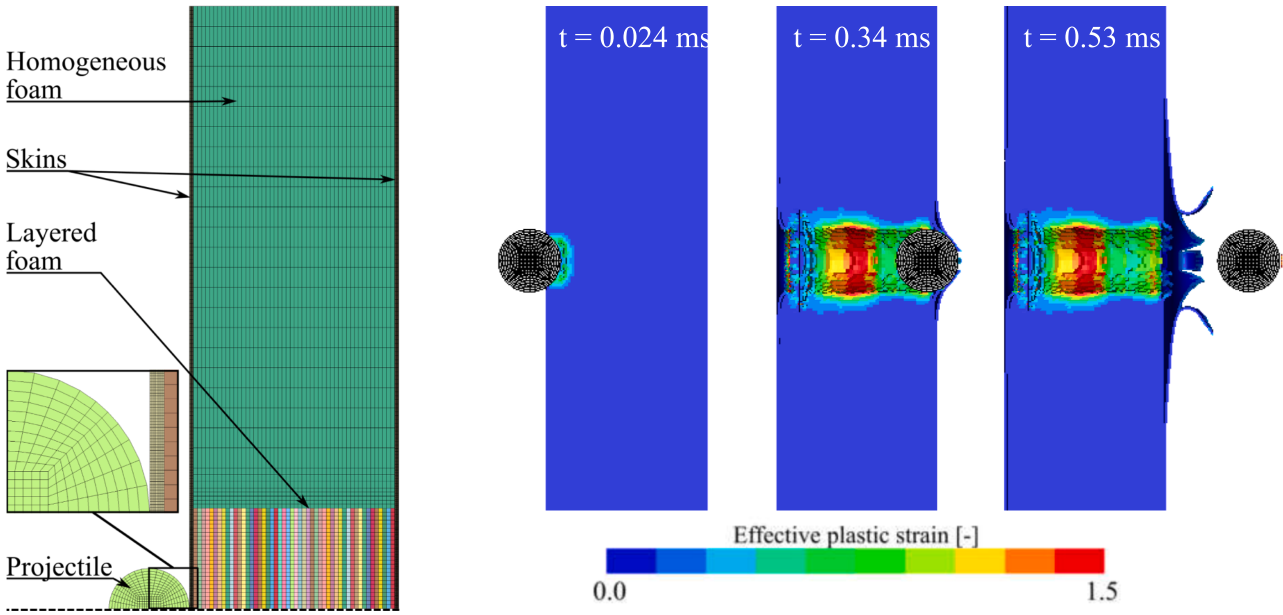

Fig. 3. Numerical model (left) and time-lapse (right) of the perforation process of the sandwich panel (v_i = 200 m/s, v_r = 154.5 m/s).

calibration of the foam core using *MAT_154, see Brekken et al. [6].

Several simulations at impact velocities between 80 and 250 m/s were carried out using the numerical model described above. The results are plotted in Fig. 2 (right) where they are compared to the experimental data. While the numerical and experimental results for the foam core only showed an almost perfect agreement, a small deviation of less than 4% in ballistic limit velocity was obtained between the numerical (v_{bl} = 110.6 m/s) and experimental (v_{bl} = 106.9 m/s) results for the sandwich panel. However, the significant fragmentation seen experimentally was not captured (compare Fig. 1 and Fig. 3 (right)). Finally, the numerical model was used to study the effect of increasing the thickness of the skins. If the skin thickness was increased to 1 and 2 mm, respectively, the ballistic limit velocity was increased to 111.5 and 128.3 m/s. Thus, increasing the thickness (and consequently the weight) of the skins by a factor of 2.5, gave a predicted increase in perforation resistance of less than 20%. A more distinct increase in ballistic performance could be achieved using a higher-strength aluminium alloy as the skin material (e.g., AA6016-T6 [10]).

5. Concluding remarks

In this study, an inhomogeneous aluminium foam was used as core material in a sandwich panel. Ballistic impact tests on the panel were conducted in a gas gun using steel spheres as projectiles, and the results were compared to corresponding impact tests on the core without the skins. Numerical models of the ballistic impact tests were established, and both material tests and XRMCT data were used in the calibration of the constitutive relations. To account for the inhomogeneity of the foam, the impact zone was modelled with 50 layers to distribute the density-dependent parameters. The main conclusions from the work are:

- A sandwich panel with thin, low-strength aluminium skins and an aluminium foam core increased the ballistic perforation resistance by 16% compared to the foam core only. This increase is roughly the same as the weight increase of the panel upon adding the skins.
- The use of XRMCT data makes it possible to include the density variation in FE models using a continuum material model for the inhomogeneous foam.
- A numerical model with constitutive relations calibrated from XRMCT data and material tests was able to accurately predict the perforation process and the ballistic limit velocity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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