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Experimental study of sandwich structures as armour against medium-velocity impacts

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A B S T R A C T

An experimental impact study has been conducted on sandwich structures to identify and improve armour solutions for aeronautical applications. The objectives are to find the best configurations, i.e. the non-perforated targets with the minimal weight and back deformations. Medium-velocity impacts (120 m/s) have been conducted using a 127 g spherical projectile. The targets are simply supported at the rear of the structure. Two potential choices of front skin have been identified for the sandwich structure: 3 mm thick AA5086-H111 aluminium plates and dry aramid stitched fabrics (between 8 and 18 plies). The dry stitched fabrics appear to be an original solution, which associates a lightweight structure and a good perforation resistance. Moreover, a strong coupling has been found between the front skin and the core. The impact tests indicate that aluminium honeycomb core associated with aluminium skins show mitigated results. However, the combination of dry fabric front skin and aluminium honeycomb show better performances than aluminium sandwiches, with a global weight decrease.

1. Introduction

Aeronautical structures and especially zones of the aircraft fuselage can be potentially subjected to foreign object impacts, like ice, engine debris or birdstriking. This study aims to identify and to optimize armoured structures against hard projectiles through experimental impact tests. These impacts are characterized by medium-velocities and high energies: 120 m/s and 1 kJ. In this paper, several criteria are chosen to select and compare the armour solutions: minimal weight and residual deformation without perforating. Sandwich structures appear to be potential armour architectures, providing an increase in bending rigidity without a significant increase in structural weight. They are currently used in numerous applications like for instance helicopter blades, ship hulls or optical benches for space applications. A complete literature review on sandwich structures subjected to impact is very difficult to establish due to the wide variety of target materials and impact conditions.

Aluminium sandwiches composed by aluminium plates as skins and aluminium cores (honeycomb or foam) are currently used against shocks in naval structures, or against impacts [1–3]. Sandwich structures using composite materials are foreseen as armour solutions, due to their stiffness and lightweight properties. Either associations of dry fabrics or interlock structures and ceramic layers, either metallic structures (mostly steel thick plates) are often used in ballistic studies. Among these materials, ceramics and steel are not chosen because their high densities do not fit to the aeronautical constraints. Thus, aluminium, composites and dry fabrics are identified as potential materials and structures considering medium-velocity impacts. Therefore, the literature revue focuses on sandwich or layered structures using these materials.

Considering aluminium plates, the literature relates that aluminium ductility can play a major role in impact resistance. For instance, Børvik et al. [4] showed that the ballistic limit of AA5083-H116 is 20% higher that the AA7075-T651 (244 m/s impact on 20 mm thick targets), which is although more resistant with a yield stress twice as high. Several material and thicknesses combinations have been tested in the literature. In ballistic impacts, the association of a ductile material as the first layer associated with a high strength material gives the best impact performances [5] (flat and conical projectiles of 200 g launched at 400 m/s on steel layers targets). The layering of aluminium or steel plates to improve impact performances has been widely studied in the literature [6–9]. However, it is difficult to establish a clear tendency. For instance, Gupta et al. [6] showed that 1100-H12 aluminium plates perform a

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better impact resistance than layered targets with the same total thickness (1–3 mm). Nevertheless, stratification seems to be advantageous with thick targets, typically around 6 mm [7]. Marrom et al. [10] as well as Radin et al. [11] compared the performances of monolithic structures and of layers in contact or separated by an air gap. They both showed that layered structures in contact give better results than monolithic structures or layered structures with a gap between each layer, for a same total weight.

Concerning the dry fabrics behaviour, Cheeseman et al. [12] made a synthetic review on the different parameters influencing the ballistic impact performances of these structures. The impact conditions as the projectile velocity, the target dimension, and the boundary conditions (aperture size [13], target dimension) are the most significant parameters. For instance, Zeng et al. [14] showed that the energy absorbed by two edges clamped Twaron targets is 4.5 times the absorbed energy in the case of total clamping (under 350 m/s). The fabric orientation at 45° shows good results by increasing the loading area and the length of the principal yarns. The fundamental parameters related to the fabric are the fibre material, the ply number and the friction properties. Fabrics made of aramid (Kevlar 49, Twaron), polyethylene (Spectra, Dyneema), PBO fibres (Zylon) are mostly used. Roylance et al. [15] showed that the cover factor is also an important parameter. It consists in the percentage of area covered by the fabric (related to the width and pitch of warp and weft yarns) and an optimal range is defined between 60 and 95% to avoid yarn sliding under the projectile. Moreover, the yarn surface properties are also to be considered as friction leads to larger amounts of absorbed energy. A study conducted by Briscoe and Motamedi [16] noted that a lubricant addiction lead to a decrease in the fabric absorbed energy. According to the authors, the role of yarn friction in the resistance against perforation and energy absorption is not totally understood yet and needs further investigations. Karahan et al. [17] and Ahmad et al. [18] studied the effect on ply number and stitching on aramid fabrics. Karahan et al. [17] showed that no significant difference in energy absorption is observed varying the stitching pattern (perimeter, 50 mm edge grids, etc). Ahmad et al. [18] showed an increase in ballistic limit with stitched targets (+8% with 2 in edges stitching compared to targets without stitching). Note that numerous experimental and numerical studies are conducted on dry fabric structures. However, multi-layered structures, or fabrics associated with other materials are rarely investigated in the literature. Moreover, the use of dry stitched fabrics within a sandwich structure is not yet studied to our knowledge.

Many studies have been conducted on sandwich structures subjected to impact [19–22]. At the onset of impact, compressive waves propagate under the projectile and provoke local out-of-plane shear damage of the skins and core crushing. In a second step, a global shear/bending deformation of the structure is observed. Note that if the initial projectile velocity is superior to the ballistic limit, the bending effect does not appear. Abrate [23] noted that few studies worked on the sandwich configurations while many of them considered the projectile parameters effects (shape, mass and velocity). This is why results are sometimes in conflict from a study to another. However, it is necessary to study a wide number of sandwich configurations in order to understand the complex coupling between facing and core which largely dictates the impact damage for a given loading. Abrate noted that the penetration resistance is mostly governed by the overall rigidity of the targets and the facing penetration resistance. In case of composite facing sandwiches fail through matrix cracks, fibre fracture and delamination. The structures also exhibit core crushing and facesheet debonding. Buitrago et al. [24] conducted impact tests and numerical simulations on sandwiches using composite facesheets (carbon fibre with epoxy resin, 2 mm thick) and an aluminium honeycomb 20 mm thick (velocities in the range of 92–548 m/s). The skins are identified as the main factor responsible for the energy absorption (respectively 46%, 13% and 41% for the front skin, the core and the back skin).

The previous synthesis showed that many studies were conducted on specific materials or structures like aluminium plates, dry fabric assemblies, etc. However, the interaction of different materials assembled in a structure is rarely addressed due to the large number of experiments necessary to identify couplings and structural effects. Moreover, contrary to ballistic or low-velocity impacts, medium-velocity impacts with high energies are few studied in the literature. This study aims to identify and compare sandwich structures subjected to medium-velocity impacts. Several assemblies of skins and core are studied to determine the respective role of each part of the sandwich and possible couplings as well as to propose ways of material and geometrical optimizations.

The experimental impact set-up, target description and impact results are given in Section 2. Then, the behaviour of aluminium sandwiches is described in Section 3, followed by the study of sandwich structures with dry fabric front skin in Section 4. The non-perforated structures are compared in Section 5. Finally, concluding remarks are given in Section 6.

2. Experimental set-up

2.1. Impact test conditions

Normal impact tests are conducted using a gas gun. A spherical projectile of 127 g and 30 mm diameter is launched at an average velocity V_{ini} of 120 m/s at the centre of the targets. The projectile is composed by a hardened steel spherical nose and shank and is supposed perfectly rigid. The cylindrical shank with 8 mm diameter and 50 mm length is screwed to the rear of the nose. The same projectile is reused for all impact tests. A high speed camera is used to measure the projectile displacement and velocity during the test by following to the painted shank. Square targets of 200, 300 or 400-mm side are simply supported at the rear by a square frame with an aperture of 170-mm side (see Fig. 1). These boundary conditions are more representative of impact on real structures such as the aircraft fuselage compared to clamping along four edges. The experimental set-up and several camera pictures are given in Fig. 1.

In the particular case of dry fabrics, the boundary conditions are defined in order to be representative of a real structure of about 600-mm side. During the impact, the primary yarns (i.e. the yarns situated under the projectile) are loaded in tension, which induces a yarn elongation. The additional distance is called de-crimping length (see Fig. 2a and b). This distance can be calculated knowing the structure size and the weave properties. When considering the fabrics used in this study (cf. Table 1) the yarn crimp reaches 0.4% for the twill fabric and respectively 0.51% and 3.5% for the plain weave in the weft and warp direction. Therefore, the de-crimping length can reach 2.4 mm in the twill fabric and respectively 3.1 and 21 mm in the weft and warp direction of the plain fabric for a 600-mm side panel. In order to represent this mechanism with smaller samples comprised between 200 and 300-mm side, a free-edges boundary condition has been chosen. Thus, the yarns can potentially slide from the target extremity, providing an additional length under the impact point (Fig. 2c and d).

2.2. Material description and targets identification

The tested sandwich structures are assembled using aluminium or dry fabric front skins. Honeycomb core of different thicknesses