EXPERIMENTAL STUDY OF SANDWICH PANEL UNDER IMPACT LOADING

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ABSTRACT

This paper aims at the study of failure behaviour of sandwich structures composed of 1mm aluminium top and bottom face sheet and cellular solid core (honeycomb, Cymat foam etc.) Impact perforation/indentation tests with a 16mm diameter indenter are performed for this purpose.

Under impact loading condition, an inversed penetration configuration is arranged. The panel target is mounted in the projectile launched at 60 m/s and hits a long steel bar with a semi-spherical nose (6m) which plays the role of perforator. Such an arrangement provides an original means to measure perforation force and velocity, with the use of the basic Hopkinson Pressure Bars principle.

A significant enhancement on piercing peak loading (related to perforation of the two skins) is observed under impact perforation compared to quasi-static case, whereas the aluminium sheet is known to be nearly rate insensitive. It is observed that the petaling failure mode (radial crack) is more likely to occur under high impact velocity and disking (circular crack) is more likely to take place at quasi-static loading.

The rate sensitivity of core materials is also examined using standard compression tests under quasi-static and impact loading. Even in the case that the core material is rate insensitive (as Cymat foams), the enhancement of piercing force is still recorded. Actually, the panel target is compressed before the indenter has pierced the top skin, which leads to a higher resistance of core materials. Numerical simulation and theoretical analysis are also performed to better understand such a complex perforation process.

1. INTRODUCTION

Sandwich panels with cellular core materials offer a high specific strength and an interest energy absorbing ability. Such properties make them a good solution for the protection of aeronautic structures from impacting foreign objects. For example, such panels are often used in front of aircrafts to prevent accidental bird strikes [1], which can cause significant damages to equipments and therefore affect their safety. Penetration/perforation resistances at high impact velocity of sandwich panels are then required to qualify different panels made of different skin materials (aluminium, fibre-renforced polymer) and cellular cores (honeycomb, foam, hollow sphere, etc.). Common penetration tests for lower velocity (<15m/s) could be performed using a drop hammer with a perforator [2-3]. The basic measurement in this case is the deceleration of the impact mass, estimated by an accelerometer. The force-displacement curves can be derived even though they are sometimes not accurate enough. However, the common testing technique at higher velocity consists in launching with a gas gun a free flying projectile against an immobile target [4-6]. Such a technique is also used in the case of sandwich panels [7-8]. The main records were velocities before and after perforation of the panel and there was a lack of whole perforating force-displacement history. One can only have a global energy absorbed during perforation [8-9] and this makes it very difficult the understanding of what was happened during high speed perforation processes. This paper presents an inversed perforation test where panels samples were launched at high velocity against an 6m long pressure bar at rest, which plays the role of perforator and at the same time force cell providing force and displacement recordings during the whole perforation process.

2. INVERSED IMPACT PERFORATION TESTING SETUP USING A 6M PRESSURE BAR

2.1 Experimental Arrangements

The main deficiency of classical free flying projectile –target perforation tests reported in the open literature is the lack of the force recording during the perforation process. An evident solution is to use an instrumented long rod as the projectile, and the piercing force is then measurable from recorded wave profiles as in the case of a Hopkinson pressure bar [10-11]. However, it was very difficult to launch a long rod at a uniform speed without frictions during the test. In general, a length of several meters is necessary because the measuring duration is determined by the length over the wave speed in the rod [12]. An alternative is to launch the target sandwich panel to strike the perforating long rod. Therefore, the proposed inversed perforation testing setup used a gas gun with a 70mm inner diameter barrel and a 16mm diameter and 6m-long rod with a semi-spherical nose at its perforating end. The rod is instrumented by strain gauges aimed at accurate force measurements during the whole perforation process. Fig. 1 shows an outline of the experimental set-up. The cylindrical target sandwich sample is launched with the aid of a hollow tube-like projectile, which is made from an aluminium tube with a welded bottom plate at one end. Two Teflon rings are screwed on the tube which allow for a small friction between projectile and the barrel of the gas gun. The cylindrical sandwich samples are mounted between the open end of the aluminium tube and an aluminium clamping ring. The fixture is realised by six uniformly distributed bolts slightly tightened. Fig. 2 provides a photograph of this projectile. The tube like projectile together with fixture system has a weight of 720 g. The gas gun can launch such a mass to a speed up to 60m/s.

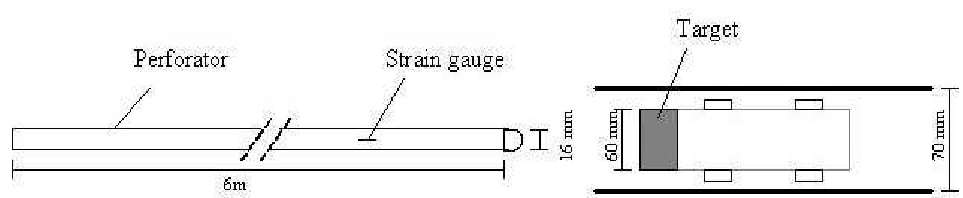

Figure 1. Experimental set-up.

Figure 2. Photo of projectile.

2.2 Measuring Technique with Pressure Hopkinson Bars

With aforementioned inversed perforation testing setup, the piercing strain impulse $\varepsilon(t)$ can be recorded by the strain gauges cemented on the pressure bars. Indeed, Hopkinson pressure bar analysis is based on the following basic assumption: the waves propagating in the bars can be described by the one-dimensional wave propagation theory. According to this wave propagation theory, the stress and the particle velocity associated with a single wave can be calculated from the associated strain measured by the strain gages.

Therefore, the piercing force and velocity time history $F(t), v(t)$ are calculated by equation (1)

$$\begin{aligned} F(t) &= S_b . E_b . \varepsilon(t) \\ v(t) &= C_b . \varepsilon(t) \end{aligned} \tag{1}$$

Where S_b ,E_b, C_b are respectively the cross sectional area, the elastic modulus and elastic wave speed of the pressure bar. However, such a theory can not describe the eventual wave dispersion effect which can introduce some error in the necessary virtual shift from the measuring point to the perforating end in time and space because the measuring point is not located at the piercing end. Therefore, the correction of this dispersion effect on the basis of the Pochhammer's wave propagation theory is systematically performed in the data processing of this wave shift [13]. The velocity of launched sandwich plate before strikes is also available, measured with two optical barriers. With this initial impact velocity, it is possible to estimate the piercing displacement. Indeed, the sandwich plated mounted on the projectile is decelerated by the piercing force measured by pressure bar. Thus, the velocity history of the sandwich sample $v_{sandwich}(t)$ and the relative displacement time history $U(t)$ can be evaluated by the equations (2) and (3) respectively.

$$v_{sandwich}(t) = V_0 - \int_0^t \frac{F(\tau)}{M} d\tau \tag{2}$$

$$U(t) = \int_O^t (v_{sandwich}(\tau) - v(\tau)) d\tau \tag{3}$$

Where M is the sum of the mass of the sandwich sample and that of the projectile. In this way, a corresponding force-displacement curve was found, which make possible a quantitative comparison between quasi-static and impact piercing behaviour.

3. QUASI-STATIC AND IMPACT PERFORATION OF STUDIED FOAM CORE SANDWICH PANELS

3.1 Sandwich Samples

The studied sandwich panels is made of 40 mm thick $AlSi_7Mg_{0.5}$ foam cores with an average relative density around 0.085 and two 0.8mm thick 2024 T3 aluminium skins. It is a potential solution in the Airbus aircrafts. The cylindrical samples of 60mm diameter were made, which have a range of weight (41-47 g) due to the heterogeneity of foam cores. The behaviour of foam cores has been investigated under quasi-static and impact loadings. Samples used in these material characterisation tests are 60mm diameter and 40mm length cylinder. Quasi-static tests are performed with universal testing machines and dynamic tests are performed with a special large diameter Nylon Split Hopkinson pressure bar in [14]. The results provide a general impression that this foam was not sensitive to the loading rate. Indeed, a large number of tests at various loading rate shows that there is a significant scatter but rate sensitivity is quite small (Fig. 3). The behaviour of aluminium skin is also performed under shear quasi-static and dynamic loading. It proofs that the aluminium is rate insensitive.

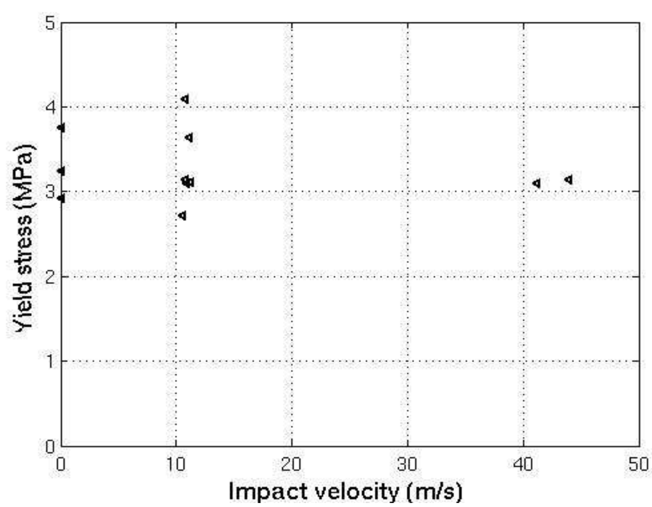

Figure 3. Rate sensitivity of foam cores.

3.2 Quasi-static Perforation

In order to obtain the same supporting condition for quasi-static and dynamic loadings, the quasi-static test is performed using the tube projectile as the supporting and fixing system. The sandwich sample mounted on the projectile is put into a universal testing machine, and a 16mm rod with spherical nose is used for perforation. The size effect is neglected because the average pore size is quite small [15]. Perforation tests are conducted at controlled speeds (0.1mm/s). Piercing forces were recorded with a force cell and displacement is obtained from testing machine measurements. Fig. 4 and Fig. 5

show post-mortem photographs of the bottom skin and the top skin respectively. One can note in particular the circular marks in these skins, which illustrate a good clumping condition. Fig. 6 shows two quasi-static perforating curves, which contain the two peak loads corresponding to the piercing of top and bottom skins. Such curves are the characteristic results for cellular core sandwich panels, reported in many previous works on various panels. In particular, the present results is compared with perforation tests with same perforator but on a 100x500mm clumping system, the peak loads are very close to each other [16]. Such a comparison provides another proof that clumping condition is well respected.

3.2 Impact perforation

Perforation tests under impact speed up to 46m/s have been performed with presented inversed perforation testing setup. Detailed post mortem images of sandwich samples under impact loading are given in Fig. 7. One of the evident differences is that the foam core has undergone a compression. Therefore, only the observation of the bottom skin failure is not affected by the stopping system (aluminium bumper used to stop the residual velocity of the projectile after complete perforation of the sample). It can be seen that, petaling can occurs under impact loading, which is different from the disking failure mode for bottom skin under quasi-static loading. The force and displacement curve under impact loading can be obtained using equation (1-3). Fig. 8 illustrates a comparison between quasi-static and impact perforations around 45m/s.

Figure 4. Bottom skin.

Figure 5. Top skin.

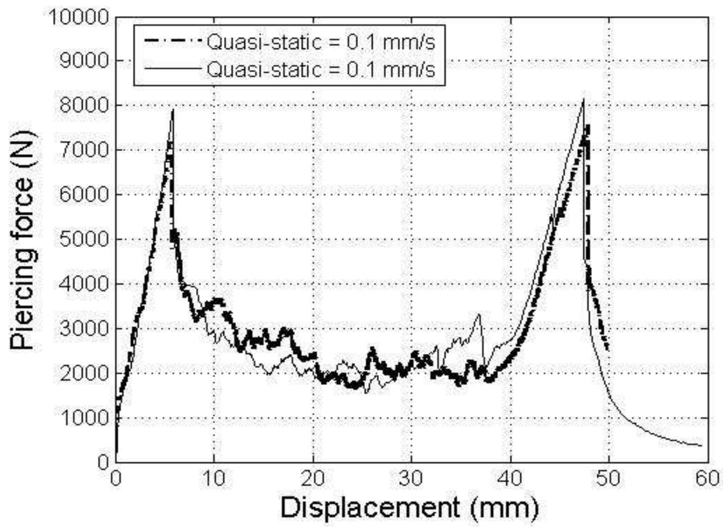

Figure 6. Two typical perforation tests.

Such comparisons of static and impact perforation tests show a significant enhancement of the top skin peak load under impact loading. However, what is the scatter of such results? Due to small number of supplied samples, only 2 impact tests around 20m/s and 2 tests around 45m/s are performed. The scatter found in impact test is quite high. However, the samples have not the same mass and the density of foam core is then different. It is well-known that the foam core strength depends much on its density [17]. On see that in these tests, the rule that denser sample has a higher resistance is respected. In order to weaken such a mass density effect, an affine correction with respect to the mass density is applied. Top skins peak loads after correction are plotted with a logarithmic value of piercing speed in Fig. 9. The enhancement under impact loading is then evident and the average enhancement under impact loading is about 20%.

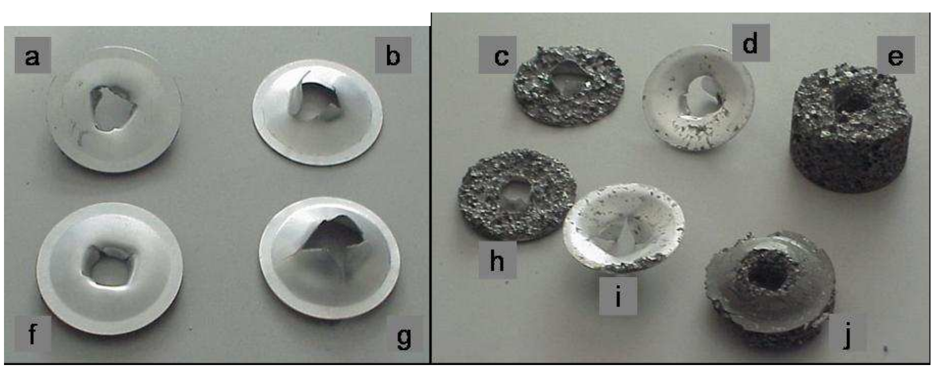

Figure 7. Post mortem images of perforated sandwich samples. Incident top skins side (a,f), distal skins side (b, g), opposed incident top skins side (c, h), opposed distal bottoms skins side (d, i), faom cores (e, j). Samples tested at 27 m/s (a, b, c, d, e) and 46 m/s (f, g, h, i, j).

4. ANALYSIS AND DISCUSSION

The enhancement found for the top skin peak loads is quite puzzling. It should not be due to the rate sensitivity of the aluminium sheet because the bottom skin peak loads are nearly rate insensitive. In order to check this argument, the piercing test on the 2024 T3 aluminium sheets mounted on the same tube-like projectile under static and impact loading are performed. It shows, in Fig. 10, that there is nearly no rate sensitivity of skin sheet. It is also noted that the foam core itself is not rate sensitive [14]. This enhancement should be due to the different interaction mechanism under static and impact loadings. Indeed, the piercing force of the top skin depends on the foam core strength. Under quasi-static loading, there exists a simple analytical model [18-19] which simplify the problem as a membrane sheet supported by rigid plastic media. Under this membrane-rigid plastic support assumption, the penetrating force depends on the tensile strength of the sheet and the equivalent supporting strength of foam cores. As the foam core have a strain hardening[14], the top skin peak load should depend on compressive strain of the foam core reached before the failure of skin sheets, and this strain before the skin failure could be different under static and impact loading, because of the inertia effect for example.

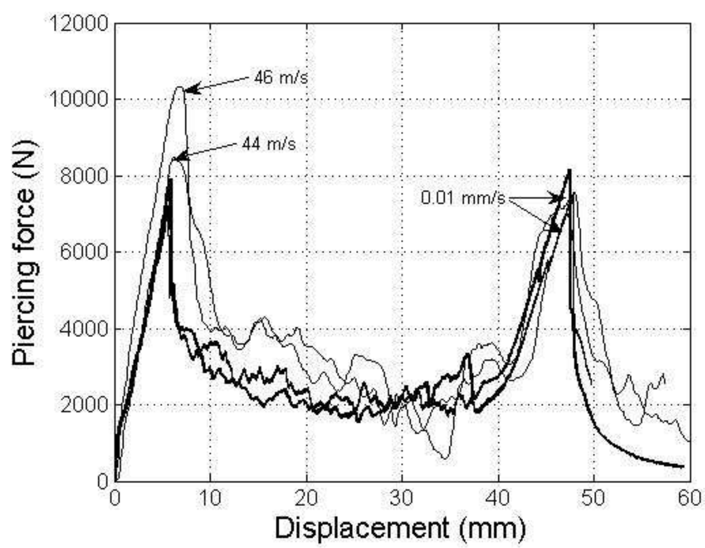

Figure 8. Quasi-static and impact piercing force vs displacement curves.

To illustrate this argument, Fig. 11 show a perforation test under static loading on the sandwich sample undergone a uniform pre-compression up to a strain of about 35% of the foam core. In comparison with the piercing force of an as-received sandwich sample, the piercing force for this pre-compressed sample has a much higher top skin peak load. Therefore, the difference of strain hardening state reached under static and impact loading due to inertia effect [20-21] leads to a higher local foam core strength under the perforator. The strength enhancement of foam cores due to their strain hardening behaviour leads to the increase of top skin peak loads. Such a concept can also explain why the piercing force into foam cores just after top skin peak load under impact is also higher than the static one, and especially why such enhancement disappears progressively thought the perforation of foam core (Fig. 8).

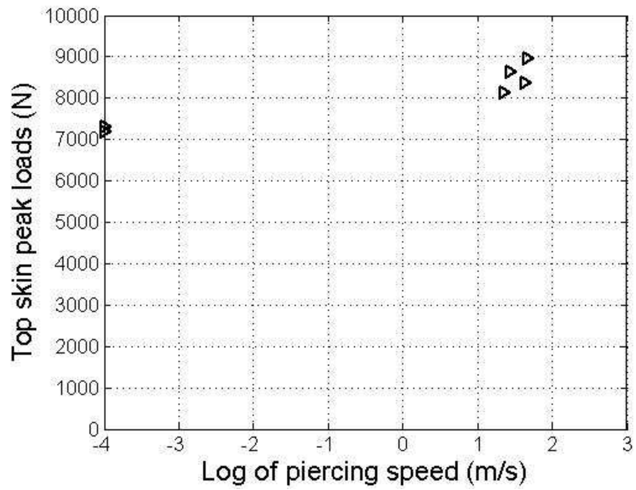

Figure 9. Density weighted of top skin peak loads.

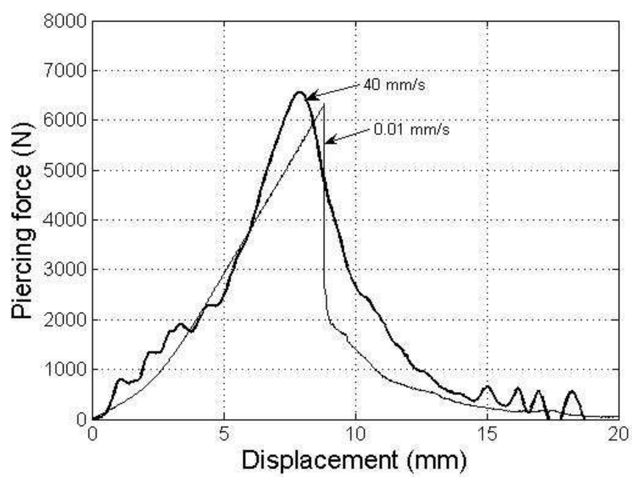

Figure 10. Piercing force-displacement curve of 0.8 mm 2024T3 sheet.

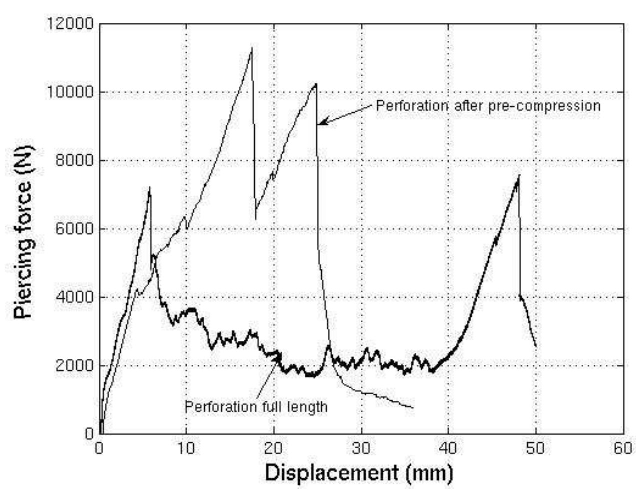

Figure 11. Piercing force for a compressed sandwich sample, compared with that of as-received samples.

5.CONCLUSION

The presented inverse perforation testing technique using a long thin instrumented Hopkinson bar allows for the measurement of piercing forces during the whole perforation process. Such measurement is missing in a classical free flying penetrator-immobile target scheme under impact loading. The present method makes it possible to compare directly impact piercing force-displacement curves with the static ones. Such test is applied to sandwich panels made of an $AlSi_7Mg_{0.5}$ aluminium foam core and 0.8mm thick 2024 T3 aluminium top and bottom skins. Quasi-static, impact tests (around 20m/s and around 45m/s) are performed. A significant enhancement of the top skin peak loads under impact loading is found. The origin of such enhancement is puzzling because the skin sheet as well as foam cores are nearly rate insensitive. A possible reason is the difference of strain hardening reached under static and impact loading due to inertia effect. Such localised foam core strength enhancement leads to the increase of the top skin peak loads.

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