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Quasi-static and impact tests of honeycomb

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Abstract. In this paper the quasi-static and instrumented compression impact testing of two kinds of aluminum-alloy honeycomb are reported. Those two types of honeycomb called Hard (H) and Soft (S) were tested. The specimens in cubical form of dimensions 60 mm × 60 mm × 120 mm were made with and without the front aluminum alloy plates (thickness 1.0 mm) cemented to the specimen two faces. The tests have been performed along the largest dimension that is 120 mm, which is parallel to the aluminum sheet profiles forming the honeycomb. A wide range of compression velocities from the quasi-static rate ($V_0 = 10$ mm/min) to the highest impact velocity $V_6 = 120$ m/s were applied. The total number of velocities applied, including the quasi-static loading, was six. Several series of tests were performed. The first two were carried out with the flat-ended strikers of specific masses, which were adequate to each impact velocity. In order to obtain an adequate displacement of crushing the condition of constant kinetic energy of a striker was assumed. In addition, conical strikers were applied with the cone angle 120° . Application of the direct impact arrangement along with properly instrumented 9m long Hopkinson bar of Nylon with diameter 80 mm enabled for a wave dispersion analysis to be applied. The crushing force versus time could be exactly determined at the specimen-bar interface by application of an inverse technique along with the theory of visco-elastic wave propagation.

1. INTRODUCTION

Aluminum honeycombs, because of its low weight and excellent absorption of energy during crushing, have found application in many engineering constructions. There has been considerable interest in aluminum honeycombs as energy absorbers because they assure large deflections with relatively constant force during crushing. However, several experimental studies on dynamic crushing of honeycombs report different effect of the initial velocity on the crushing force. One factor that may contribute to force variation are inertia effects introduced via large lateral deflections during buckling of an elementary cell [1,2]. This problem involves large lateral deflections and structural dynamic plasticity. Certainly, the wall thickness of elementary cell is probably the main factor in inertia contribution to the variations of crushing force at different impact velocities. Since in cells some air pockets may rest during impact compression, this effect may also contribute to the total force during honeycomb deformation.

It is not clear at present to which extent the inertia plays a role in the level of the crushing force when the impact velocity is increased. Typical range to be tested spans velocities from ~ 1.0 m/s to ~ 200 m/s or even higher. Concerning the quasi-static compression tests on variety of honeycombs made of different aluminum alloys a typical load-displacement curve $F(\delta)$ shows approximately a straight line ending with a sharp force peak as a signal of structural collapse followed immediately by a series of load fluctuations. The load peak, called also the compressive strength, is sensitive to the rigidity of the loading frame. It is not clear whether its amplitude depends on velocity at which loading occurs. In the literature different conclusions are reported on the velocity effect on the compressive strength. It is known that the series of force variations following in the form of regular load peaks is related to consecutive folding of the layers of elementary cells. The mean level of force during the crushing process remains relatively constant. The force of crushing, called also the crushing strength, is substantially lower than the peak force. Typical behavior of compression test on one of specimens tested is shown in Fig.1. When a specimen is well aligned an abrupt force collapse is observed with an intense energy release in the loading arrangement.

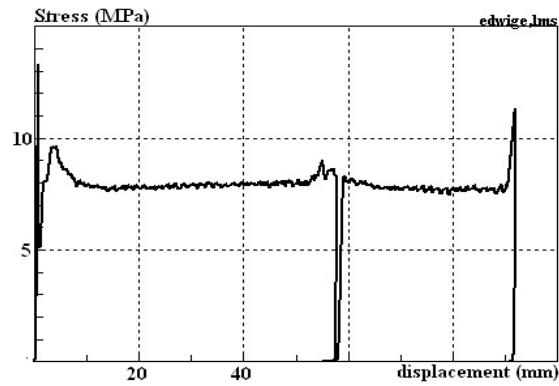


Figure 1. Results of quasi-static force-displacement curve obtained during compression test, displacement velocity 0.03 mm/s, initial specimen length 120 mm. (Specimen: Hard H).

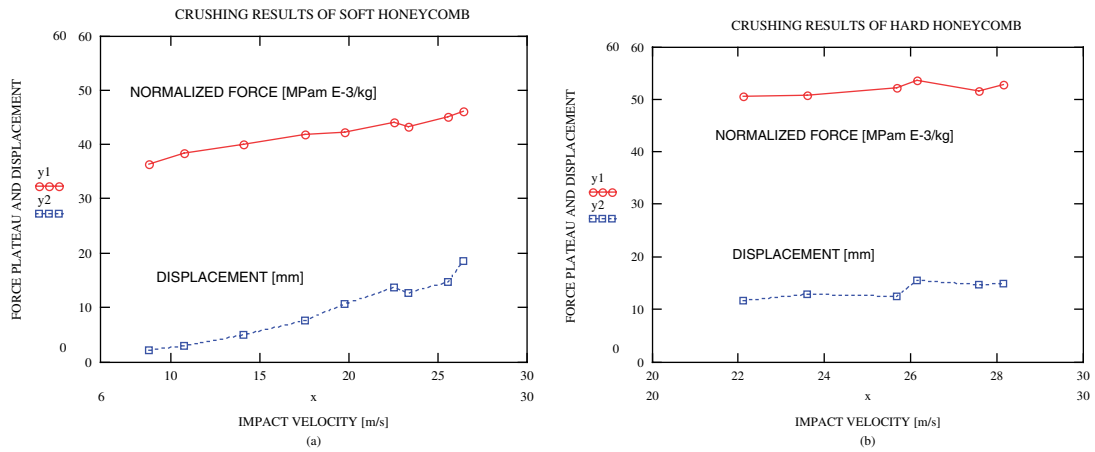


Figure 2. Reanalyzed data reported in [3] for soft and hard honeycombs.

Because of technical difficulties in precise measurement of the force-displacement during crushing of honeycombs and uncertainties in separation of the intrinsic material rate sensitivity and contribution of the local buckling inertia of each elementary cell to the global behavior the results of experiments are widely different. It is out of scope of this paper to review all available results. It may be mentioned experimental study reported in [3] on impact loading of both bare honeycombs and sandwich plates with honeycomb cores. Blunt strikers with diameter ~ 47 mm impacted specimens with velocities from 10 m/s to 40 m/s of smaller cross section supported by simply and rigid supported backing. An increase of about 20% to 50% in the plateau of force over the range of impact velocities was found. Another results of investigation were reported in [4] where quasi-static and impact crushing of several designs of honeycomb were tested in compression at velocities up to 27 m/s. An advanced system of measurements permitted to determine all main parameters of crushing. A significant increase of the peak load called the “bare compressive strength” was observed. Such compressive strength increased 74% in relation to the quasi-static value when the impact velocity was increased up to 27 m/s. However, the rate sensitivity of the stress plateau was lower. In order to discuss certain features some data reported in [3] for two kinds of honeycomb have been reanalyzed and the result is shown in Fig.2 in the form of the normalized crushing plateau versus impact velocity. The force has been normalized by the honeycomb density.

The test results shown in Fig.2a clearly indicate an existence of the positive rate sensitivity. In contrast to the substantial rate sensitivity of the peak force the estimated rate sensitivity for the force plateau in the range of impact velocities up to 27 m/s is $\sim 30\%$. In the case a harder honeycomb the rate sensitivity is practically zero and the path of crushing rests also constant. This example demonstrates that variety of possibilities is available in honeycomb designing.

Another experimental technique in testing of aluminum honeycombs up to ~ 300 m/s was reported in [4]. The specimens of diameter 45 mm and length 30 mm were launched from a gas gun on to Hopkinson bar. In order to measure the force exerted by a specimen during collision the Hopkinson bar of diameter 50 mm and length 2.4 m was applied. The specimens were designed with or without backing disks. Since the aluminum backing disks attached to specimens had a mass significantly greater than the specimen it was assumed the measured pulse was due to the mass of the disk. By neglecting the mass of honeycomb specimens an approximate crushing force versus displacement of crushing could be estimated by integrating the equation of motion of the disk mass. It was found a significant effect of inertia on the plateau stress. The Dynamic Intensification Factor (DIF) at crushing velocity ~ 300 m/s was found as high as ~ 12 .

Conclusions after this brief review of some test results clearly indicate on uncertainties of experimental techniques as well as of quantitative estimation and more precise theoretical sources of rate sensitivities observed in honeycomb crushing.

One of the tasks of the experiments reported herein was a study of rate effects on the crushing force plateau for two honeycombs, that is softer and harder. Another area of interest was the mode of cell deformation and collapse. Finally, the capacity of energy absorption was also a point of interest.

2. SPECIMENS AND TEST PROGRAM

The main task was the quasi-static and instrumented compression impact testing of two kinds of aluminum alloy honeycomb. Those two kinds of honeycomb are called Hard (H) and Soft (S). The specimens in cubical form of dimensions 60 mm \times 60 mm \times 120 mm were made without and with the aluminum alloy plates of thickness 1.0 mm cemented to the specimen two faces. The compression tests have been performed along the largest dimension that is 120 mm which is parallel to the aluminum sheet profiles forming the honeycomb. The number of cells in 60 \times 60 mm² cross section is $N_S = 360$ and $N_H = 415$. The specific densities of each material are $\rho_S = 131$ and $\rho_H = 156$ (kg/m³).

A wide range of compression velocities from the quasi-static one, $V_0 = 10$ mm/min, to the highest impact velocity $V_6 = 120$ m/s was applied. Specific values of impact velocities applied in crushing tests were as follows: $V_3 = 30$ m/s, $V_4 = 60$ m/s, $V_5 = 100$ m/s and $V_6 = 120$ m/s. Thus the total number of velocities, including quasi-static one, was six. Since two types of specimens were prepared made of two kinds of honeycomb (without and with front plates) four series of tests have been performed. Specimens S and H without the front plates were tested at V_0 , V_3 , V_4 , V_5 and V_6 (five velocities) and at each velocity at least two good tests have been performed. The same program was applied for both PS and PH specimen versions (specimens with the both-end plates). The total number of tests was 40. For all those tests flat-ended strikers were used.

In addition, tests were carried out with the conical punches (quasi-static loading) or strikers with the front angle 90° and 120°. In that case only PS and PH specimens were tested. Tests with the conical punches or strikers, that is PH and PS specimens, were carried out at three velocities: V_0 , V_4 and V_5 . The total number of tests within the framework of the program was 82.

The main task has been to determine the mean crushing force of two kinds of the honeycomb versus the impact velocity and compare results with the quasi-static values. The tests with the conical punch or striker were designed to test resistance to penetration when a sharp body impacts the plate-protected honeycomb. Several characteristic parameters were determined after the tests, like the impact velocity, the mean crushing force derived by the means of the energy conservation, the crushing stress determined independently by electronic measurements. Another parameter that can be determined is the energy of

crushing par the unity of the crushing distance. All quantities determined are discussed in detail in the following parts of the paper.

3. REMARKS ON EXPERIMENTAL TECHNIQUE

The Laboratory of Solid Mechanics of Ecole Polytechnique is well equipped to perform variety of tests at high rates of deformation and impact. Because the honeycomb specimens are relatively long ($l_0 = 120$ mm) the only available experimental arrangement could be based on the “direct impact” principle, [5,6]. In that case a specimen is placed in the front of a long measuring bar (Hopkinson bar) and is loaded by impact of a striker with pre-defined velocity. The relatively large transversal specimen dimension (60 x 60 mm) imposes dimension of the setup. On the other hand, the large axial displacements during specimen crushing impose special technique of measurements. Thus, at the lowest impact velocity $V_3 = 30$ m/s and the crushing distance 60 mm, that is half of the initial length of specimen the time interval of test is relatively long, $t_m = 2.0$ ms. Such conditions of testing need a device capable to measure the crushing force as a function of time without perturbation during time interval at least 2.0 ms. On the other hand, at impact velocity $V_6 = 120$ m/s, the time interval of crushing is of the order 500 μ s. Optimal conditions of testing concerning a wide span of the crushing time were assured by application of a long instrumented Hopkinson bar made of Nylon 80. The Hopkinson bar of DIA 80 mm and total length of ~ 9.0 m with its low wave speed C_0 close to 1700 m/s enables for a long measuring time without perturbation up to 20 ms. The measuring bar has been instrumented with three SR stations with the signal conditioners (three Wheatstone bridges and amplifiers). The band pass of the measuring strain was 1.0 MHz. The SR stations were placed at different distances from the impact face of the bar. In addition, the mass velocity could be measured in the bar by an optical non-contact displacement gage. Finally, at the end of the bar a piezo-quartz gage of force was attached. Such instrumentation has permitted for a complete control of the crushing force as a function of time with the triple checking. The impact velocity of specially prepared strikers was measured by another independent non-contact optical gage Z in Fig.3. All six electric signals were recorded in time by a fast digital acquisition card (sampling rate up to 1.0 MHz) plugged to a PC. The five-channel data has been stored in the HD of PC for further analyses. A scheme of the experimental arrangement is shown in Fig.3.

In Fig.4 is shown a picture of specimen backed by the Hopkinson bar; 1- specimen, 2 – Nylon Hopkinson bar, 3 – specimen guide, 4 – end of barrel, 5 – striker.

Since the Hopkinson bar of diameter 80 mm was used as a measuring device, the strikers diameter had also the same dimension. Such necessity imposed specific dimensions on strikers, especially for definition of a correct mass suitable for each impact velocity. Because the mean crushing force \bar{F} could be estimated from the quasi-static tests and the crushing displacement was defined as $l_0/2$, that is 60 mm, from the condition of energy conservation $W_p = W_k$, where W_p and W_k are respectively the energy of plastic deformation and the kinetic energy, the mass of a striker m_p could be calculated for each velocity V_0 . Thus the energy balance and the striker mass m_p are given by:

$$\frac{1}{2} \bar{F} l_0 = \frac{1}{2} m_p V_0^2 \quad \text{and} \quad m_p = \frac{\bar{F} l_0}{V_0^2} \quad (1)$$

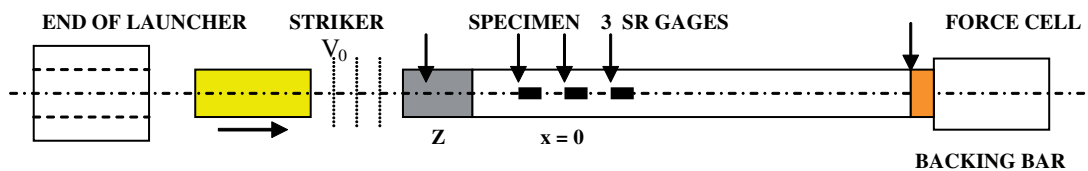


Figure 3. Scheme of experimental arrangement, SR – Strain-Resistance gages, Z – Optical displacement gage.

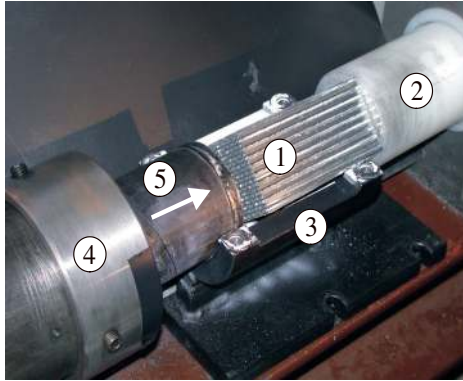


Figure 4. Arrangement of striker, specimen and Hopkinson bar.

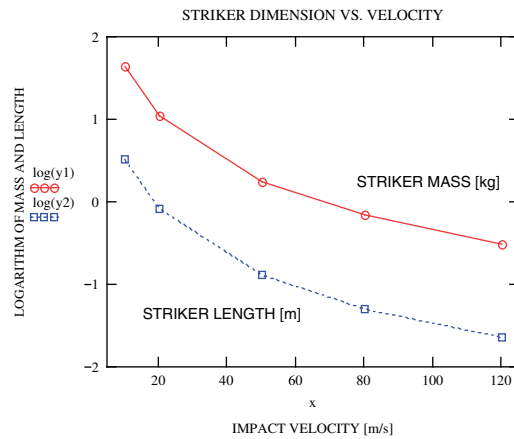


Figure 5. Necessary masses and lengths of Al strikers for air gun barrel 80 mm.

It appears from the constant kinetic energy condition that the striker mass must be diminished in proportion to $1/V_0^2$. If a solid striker of Al-alloy and diameter 80 mm is assumed then at velocity $V_0 = 120$ m/s the length of such striker would be ~ 30 mm ! When the mean plateau of the crushing stress is assumed 6.0 MPa the estimated mass of an Al striker and the striker length as a function of the impact velocity V_0 is shown in Fig.5.

It may be noted that the scales of mass and diameter are logarithmic. For example, the striker length Therefore it was decided to construct an individual striker for each velocity. For low velocities a solid steel striker, for intermediate velocities a striker made of Nylon 80 and for high velocities strikers combined with aluminum plates attached to tubular cardboards. A picture of combined striker with specimen is shown in Fig.5. During a dynamic crushing test the cardboard tube is destroyed but not the front aluminum plate. A specimen before each test is lightly attached in the front of the Hopkinson bar by a double side glue tape in a special tubular holder. During each test the front of a striker is guided in a perforated holder. The holder assures that a specimen faces remain parallel and after each test the permanent distance of compaction $\Delta l = l_0 - l_R$ can be determined. The initial and remaining specimen lengths l_0 and l_R are measured before and after each test in two perpendicular directions and the mean values are next applied to determine the mean crushing force by writing that energy is dissipated in plastic work into the specimen, provided that friction between the striker and the guiding device could

be neglected. It will be shown that this approximation is not correct. Thus, the mean force would be given by

$$\bar{F} = \frac{1}{2} \frac{m_p}{\Delta l} V_0^2 \quad (2)$$

All quantities in Eq.(2) are determined before and after the test. The mean force of crushing can be compared with the force $F_b(t)$ determined at the interface specimen-bar after analysis of the wave process in the Nylon Hopkinson bar. According to standard procedure, [5,6], the force $F_b(t)$ at $x = 0$ is defined by Eq.(3) when the transmitted wave $\varepsilon_T(t)$ is measured by a SR gage at the distance x_g , thus

$$F_b(t) = \frac{\pi d_b}{4} \rho C_0^2 \varepsilon_g \left(t - \frac{x_g}{C_0} \right) \quad (3)$$

where d_b , ρ , ε_g are respectively the bar diameter, the bar density and strain measured by a SR gage, C_0 is the elastic wave speed in the bar. This direct measurement shows that the values deduced from equ. (2) are overestimated by some 10%, proving that a direct force measurement is really worth being done. The interface displacement of bar-specimen is given by

$$\delta_b(t) = C_0 \int_0^t \varepsilon_g \left(\zeta - \frac{x_g}{C_0} \right) d\zeta \quad (4)$$

Finally, when the force $F_s(t)$ acting on the striker-specimen interface is known the crushing displacement can be determined as

$$\delta_s(t) = \int_0^t \left(V_0 - \frac{F(\zeta)}{m_p} \right) d\zeta \quad (5)$$

The net crushing displacement is $\Delta(t) = \delta_s(t) - \delta_b(t)$. When compared with the post-mortem measured one, a significant difference is observed. Considering the conservation of momentum, the momentum in the wave is found greater than the nominal momentum of the striker, in particular for tests at highest speeds. It is checked that the difference is due to a reminding pressure acting on the striker during the crushing process. When taking account of this pressure estimated from the measured momentum, as shown in Fig.6, a good agreement is now found between both crushing displacement measurements.

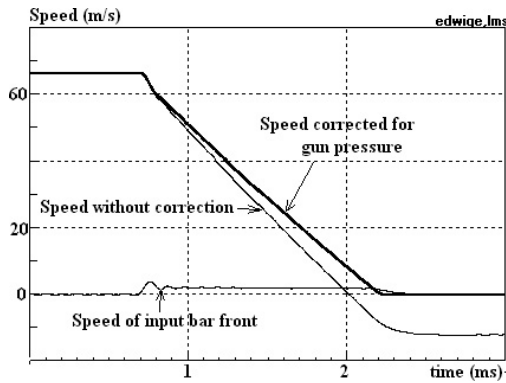


Figure 6. Variations of velocities of striker and front of bar during crushing versus time, H-specimen with plates, $V_0 = 67$ m/s.

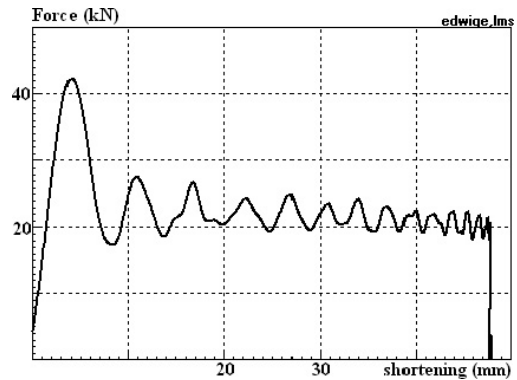


Figure 7. The final result force-displacement for H-specimen with plates, the same initial conditions as in Fig.6.

Since polymers show higher wave dispersion than metals via two contributing components: the energy dissipation due to visco-elasticity and geometrical dispersion due to radial inertia, theoretical analysis of those effects in determination of the force on the specimen-Hopkinson bar interface is necessary. The elastic waves are distorted. This is why three SR stations at different distances were cemented on the Hopkinson bar.

4. REMARKS ON WAVE DISPERSION IN VISCO-ELASTIC BARS AND FINAL TEST RESULTS

In order to analyze the wave dispersion and to obtain corrected data of $F_b(t)$ and $\delta_b(t)$ after SR gage measurements the method of convolution was applied, [7]. Because the method of convolution is already published, it is out of the scope to discuss here in details such procedure.

After analysis of all experiments the final results are shown in Figs 8 and 9. In Fig.8 results for soft specimens with and without plates are presented. In Fig.9 presentation is similar. It is clear that the velocity effect on the stress of crushing plateau is very weak for *all* types of specimen. The stress peaks seem to be also velocity-independent, besides results shown in Fig.8b. Of course the stress is defined as the mean force divided by the specimen area.

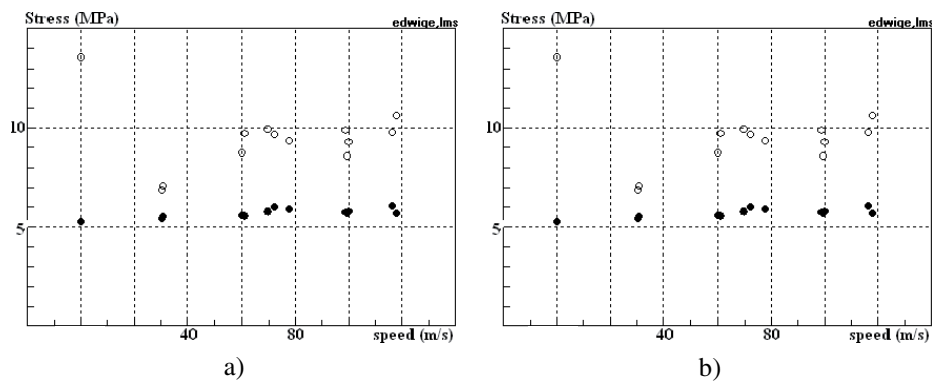


Figure 8. Stress versus impact velocity; (a) - soft specimens S without plates; (b) – soft specimens with plates, QS is the quasi-static rate.

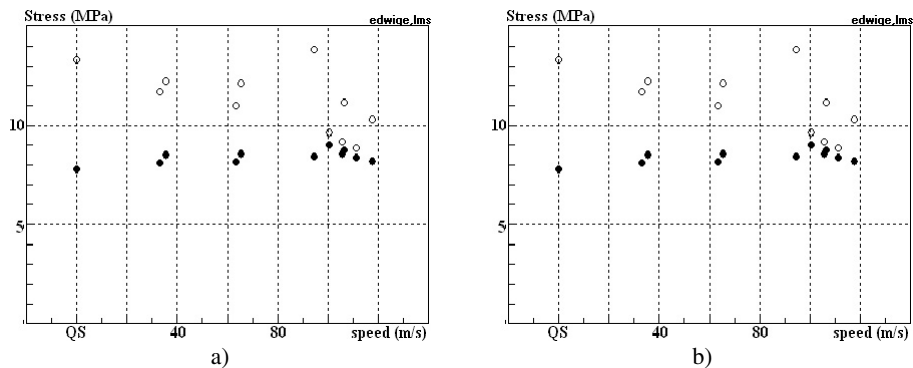


Figure 9. Stress versus impact velocity; (a) – hard specimens H without plates; (b)- hard specimens with plates.

5. CONCLUSIONS

Because of very reliable method of signal measurements and its analyses an estimated dispersion of results, that is stress is not larger than $\pm 3.0\%$. Therefore the rate effects for both materials tested are insignificant up to ~ 120 m/s. It is true that the aluminum foil used in those materials was relatively thin so the lateral inertia effects during cell folding is estimated small. It is well known, on the other hand, that the rate sensitivity of aluminum alloys are practically zero up to strain rate $\sim 10^4$ s⁻¹. The local strain rate in the plastic hinges during folding is much lower in the type of honeycombs tested than 10^4 s⁻¹. Since some researchers report a high velocity sensitive effects on crushing stress, further studies are of importance in that direction.

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