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MECHANICAL BEHAVIOUR OF HONEYCOMB CORE UNDER DYNAMIC L-W SHEAR-COMPRESSION LOADING: DEVELOPMENT OF AN EXPERIMENTAL CHARACTERIZATION DEVICE

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ABSTRACT

The mechanical properties of honeycombs are well known in pure compression and pure arbitrary L or W shear orientation. However, sizing such structures under combined shear-compression solicitations remains a complex task due to a lack of data caused by the lack of suitable experimental characterization devices. In this work, a new experimental device is designed in order to induce combined both quasi-static and dynamic compression-shear solicitations in the core. A first experimental quasi-static campaign using the developed device is then presented. The influence of the loading shear orientation angle, in L-W plane, upon the mechanical response of the studied Nomex® honeycomb is highlighted and quantified.

Keywords: sandwich structure, material characterization, combined solicitations, dynamic solicitations.

INTRODUCTION

Sandwich panels with honeycomb core are often used in aeronautical structures since they provide high specific stiffness and strength characteristics. In helicopter applications, some panels of the air-frame can be subjected to normal or oblique impacts leading to significant damage. Due to the out-of-plane and in-plane angles of impact and to the shape of the curved panels, a wide variety of loading can occur on the cells of the core. As a result, numerous combinations of out-of-plane compression and shearing in arbitrary L-W direction can be induced, increasing the need of knowledge to size the structures.

In the last 50 years, the quasi-static mechanical behavior of aluminum and Nomex® honeycomb cores has been extensively studied experimentally. However only limited number of studies dealt with dynamic behavior.

For pure compression and shear solicitations, many articles are available for any type of cores. Compression behavior is usually tested by a flatwise compression test [1-2]. On the opposite, many ways to induce a shear deformation on the core have been investigated such as three point bending [3], double lap specimen [4] or ASTM plate shear [5].

Combined compression-shear loadings are more rarely studied in literature. Several ways to induce this type of loadings in the core are available: Arcan apparatus [6], specific angle device [7] or mixed shear-compression loading device [8].

Even less common are the studies dedicated to the mechanical response under various out-of-plane L-W shear-compression ratio. One can cite Zhou et al. [6] who made a focus on Nomex® honeycomb under quasi-static combined solicitations and Tounsi et al. [8] who studied

aluminum honeycomb under quasi-static and dynamic combined solicitations using the Hopkinson bars set-up.

In this work, a new experimental device dedicated to the characterization of honeycomb core with out-of-plane compression and L-W shear couplings is proposed. Both quasi-static and dynamic solicitations are accounted for and a special attention is paid to the minimization of edge effects by specifying suited specimen dimensions.

DEVELOPMENT OF AN EXPERIMENTAL DEVICE

Hexagonal Nomex® honeycomb core of thickness 25 mm, core 3.17 mm and density $48 \text{ kg}\cdot\text{m}^{-3}$ is investigated in this study. ASTM 273 standard recommends a length to height ratio of 12 of the tested specimen. To minimize the dimensions of the experimental device while avoiding penalizing edge effects, a parametric study on the size of the specimens was carried out. A specific elastic finite element model, relying on a discretization of the walls of the honeycomb with shell elements, led to the conclusion that less than 2.5% of relative error is committed on the obtention of the shear modulus of the specimen for a length to height ratio bigger or equal to 6. Therefore, the dimension of the specimen was set to $15 \times 50 \times 90 \text{ mm}$. The core material is stabilized with two skins made of two plies of prepreg carbon fibers bounded with an adhesive glue film.

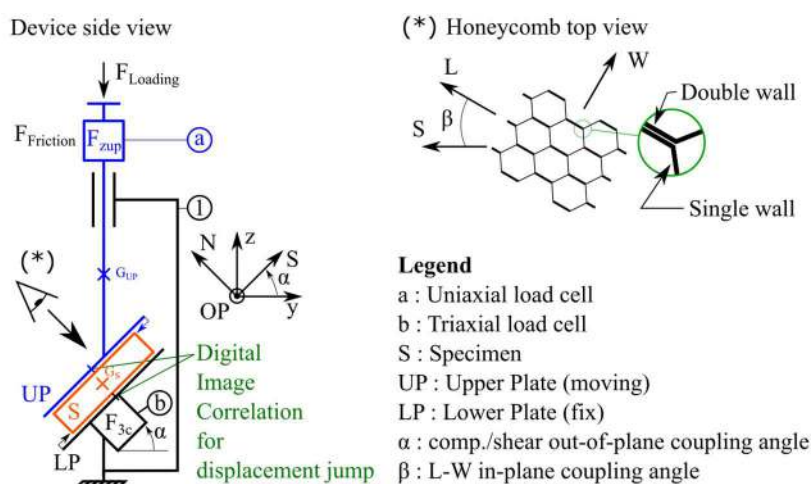


Fig. 1 – Principle of the developed experimental device.

In order to induce a combined shear-compression loading into the tested core, the specimen is placed between a lower fixed plate and an upper moveable plate both orientated with a specific angle α of 45° (Figure 1). The parallelism of both crushing plane is self-ensured by the sliding pivot connection of vertical axis between the upper plate and the fixed frame connected to the lower plate. By this connection, the test fixture converts the applied vertical displacement to both normal and shear resultant forces on the specimen. The center of gravity of the moveable head and the tested specimen are aligned with the force path to minimize inertial coupling during the acceleration phase. A 9367C Kistler triaxial load cell placed under the lower plate allows the direct measurement of the shear (F_S), compression (F_N) and out-of-plane shear (F_{OP}) force applied to the specimen (Figure 1). To protect the triaxial load cell, its position in the device is carefully chosen in order to minimize the induced momentum. The relative displacement between the upper and lower plate is extracted using Digital Image Correlation (DIC) method and the in-plane rotation of each plane can be checked and used as a parallelism indicator. Therefore, the shear and compression force versus displacement curves can be extracted.

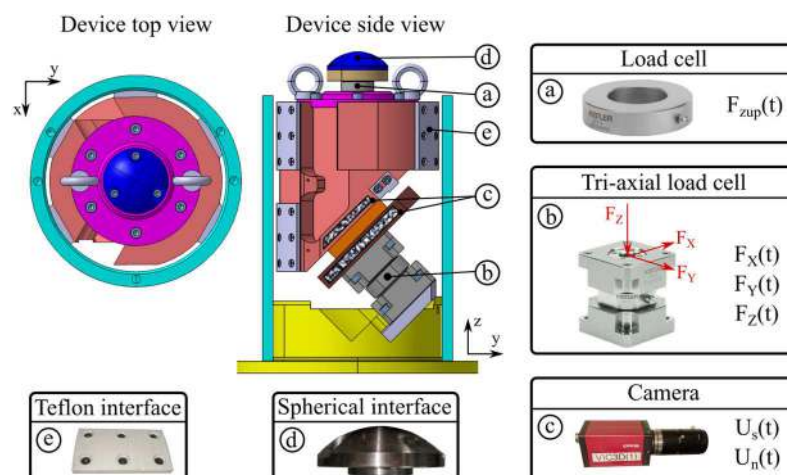


Fig. 2 – Design of the developed experimental device.

In order to avoid any momentum introduction into the testing device, a spherical metallic interface is installed under the actuator as shown in Figure 2. The sliding pivot connection between the fix and the moveable parts is ensured by a cylinder to cylinder connection with Teflon interface in the aim of reducing the friction coefficient.

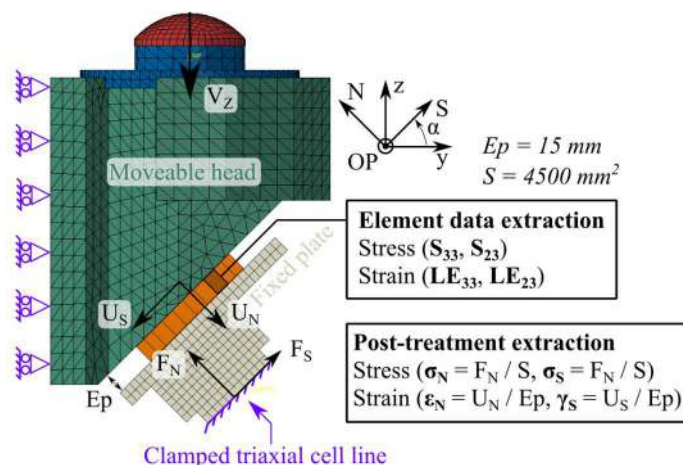


Fig. 3 – Finite element model of the testing device.

To ensure the capability of the developed device to extract the macroscopic compression and shear stress strain curve with the extracted physical value of the device, a 3D finite element model of the apparatus using Abaqus/Explicit, presented in Figure 3, was developed. The specimen is modeled as a homogenous equivalent material by the use of a user material law composed of an elastic phase followed by a plateau phase in compression and a pure elastic behavior in shear. The selected material properties of the specimen are based on the constructor datasheet of the studied honeycomb.

The upper and lower nodes of the specimen are kinematically constraint to, respectively, the nodes of the upper moveable head crushing plane and the lower fixed plate. The displacement of the moveable part is extracted from a nodal tracking while the force, applied to the specimen, results in the sum of the nodal forces of the clamped triaxial cell line. The stress-strain data extracted from element measurement is compared to the stress-strain data calculated with the measured forces (F_N and F_S) and nodal displacements (U_S and U_N). In order to check the global response of the system under quasi-static and dynamic loading, the FEM analysis is made for two vertical loading velocity V_z .

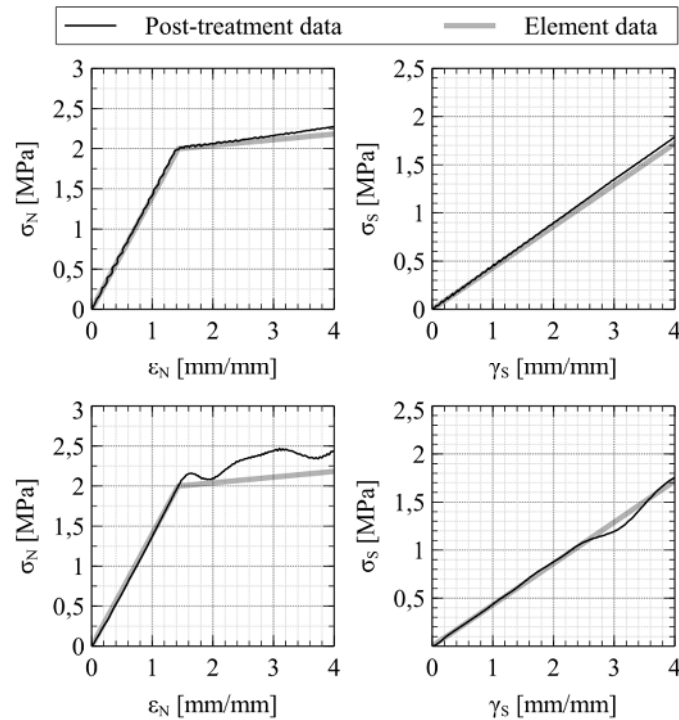


Fig. 4 – Strain/Stress curves obtained with the finite element model of the testing device.

The stress-strain curves obtained from the element extraction and the post-treatment data extraction are compared in Figure 4. The maximum error observed on the elastic modulus extracted from the linear part is less than 2%, while the compression plateau is over estimated by less than 4%. These differences can be explained by the elastic deformation of the material between the lower skin of the specimen and the force measurement location.

Once the plateau value is reached, a wave phenomenon can be observed on the calculated stress-strain curve during dynamic loading. This observation is correlated with visual observation of cyclic loading waves going through the specimen. Regardless of this physical observation, no dynamic disturbance related to the developed apparatus architecture was found.

Despite these variations, we can conclude that the model provides a good estimation of the macroscopic mechanical response of the specimen using the post-treatment data for both dynamic ($V_Z=8$ m/s) and quasi-static ($V_Z=100$ mm/s) loadings.

QUASI-STATIC EXPERIMENTAL CAMPAIGN AND RESULTS

The experimental apparatus is mounted in a 100 kN Instron compression machine driven with a vertical displacement speed of 4 mm/min. In this campaign, 5 different angle β (in-plane orientation of the specimen relatively of the shear loading direction) were tested. To guarantee the relevance of the results, 3 tests have been done for each β configuration making a total of 15 tested specimens. In order to present the results clearly, one on three representative test results will be presented for each tested configuration in this paper. The obtained force-displacement curves are presented in Figure 5. Each β configuration test matches with a color.

The compression force component of each configuration matches with the general shape of pure compression test for Nomex® honeycomb material found in the literature [2,8]. At first, a linear elastic behavior can be observed before a load peak. At this stage, a macroscopic buckling of the cells can be observed and leads to the drop of the load and to the loss of stiffness of the

tested structure. The post-peak region is characterized by a plateau representing the progressing post-buckling collapse of the cells. This collapse eventually results in to the densification phase visible by the exponential increase of the load.

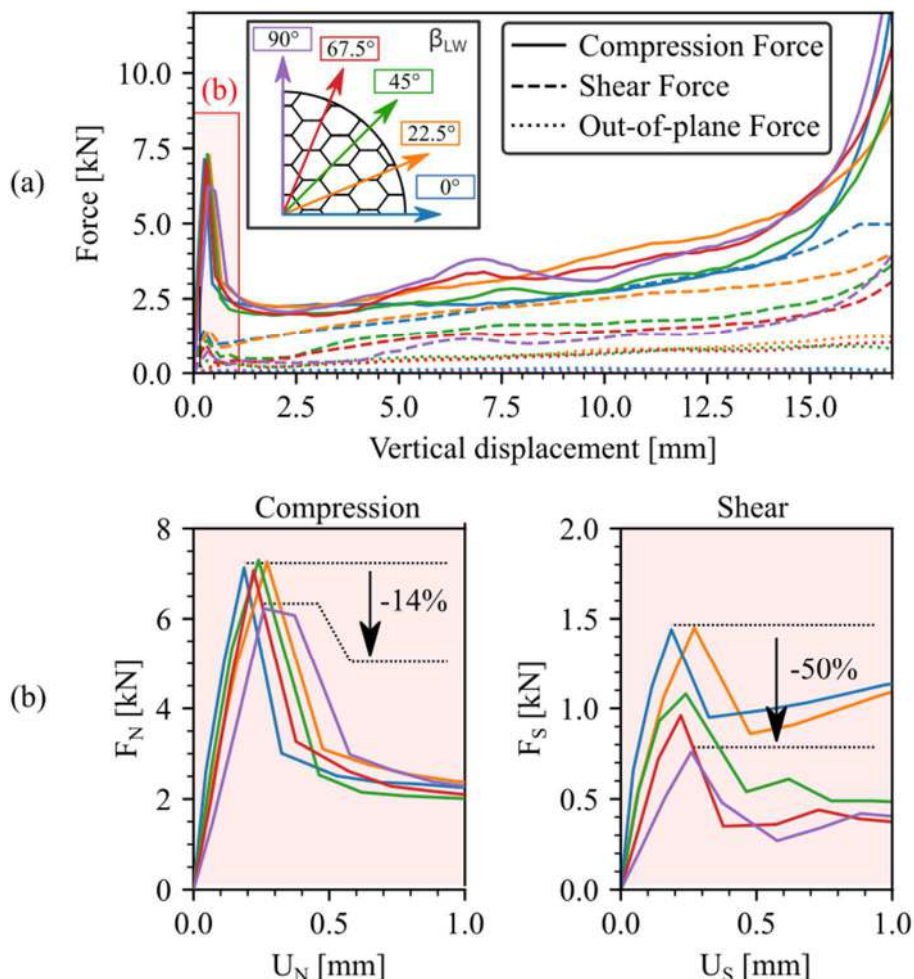


Fig. 5 – Quasi-static experimental force-displacement curves obtained for each tested β configuration.

Equally to the behavior shown in the compression force, the shear force increase linearly and drops after the load peak to reach a plateau (Figure 5b). The load drop after the peak is not generally observed during pure shear tests [3]. This tends to conclude that the collapse of the cells walls under this configuration of shear-compression test is mainly driven by the compressive collapse of the tested honeycomb.

In the light of the results, it can be seen that for the shear component, the more the angle β of the specimen tends towards 90°, the less: (1) the post-peak drop is brutal, (2) the load peak value is high and (3) the slope of the linear part representing the stiffness of the specimen is low. These observations are in accordance with Rodriguez-Ramirez et al. 2018 [3] and can be explained by the decreasing shear remaining contribution of the honeycomb double walls when β increase. On the contrary the influence of the β is less significant on the compression force component.

This conclusion is clearly visible when a closer look is taken to the peak force values. Figure 6 shows the evolution of the shear and compression peak values in correlation with the in plane shear orientation β of the tested specimens. The evolution of the shear value is clearly correlated

to the β orientation and drops to 40% for the $\beta = 90^\circ$ configuration compared to the $\beta = 0^\circ$ configuration. Moreover, this value remains stable for $\beta < 45^\circ$ configuration and starts decreasing for $\beta = 45^\circ$. Concerning the normal component, apart from the drop of 10% for the $\beta = 90^\circ$ configuration, no clear tendency of β on the peak value can be extracted. These observations tend to say that the mechanical strength of the tested Nomex honeycomb is stable for $\beta \leq 22.5^\circ$ and start to decrease once this stage is reached.

Moreover, it can be noted that the measured peak values are logically lower than the normal and shear values found in the constructor datasheet under uniaxial solicitations of respectively 25% and 55%.

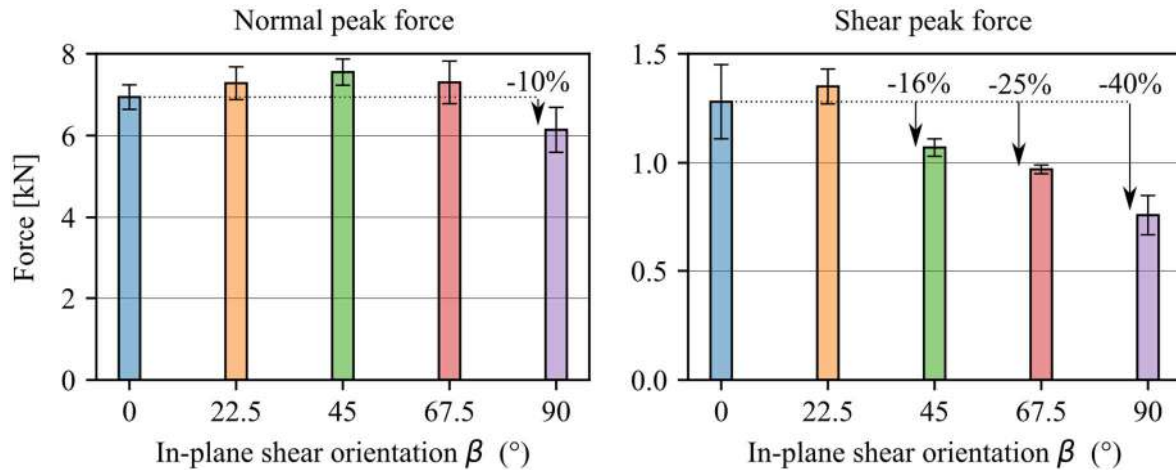


Fig. 6 – Normal and shear peak value components of the tested configurations.

The obtained results also highlight an oscillation phenomenon on the force displacement curves as illustrated in Figure 7 for the $\beta = 90^\circ$ configuration. This can be explained by the following events: (1) at t_0 , the honeycomb edges are undamaged and aligned. (2) At t_1 , the imposed displacement has made the edges buckled at the middle while the bottom and the top parts of the edges, stabilized by the resin and the glue film corners [5] are still perpendicular to their respective skins. At this stage, the Nomex[®] paper starts to tear. (3) At t_2 , because of the compaction induced by the compression force and the shear displacement, the upper edges are aligned with their neighboring bottom edges, therefore, the structure regain temporarily some stiffness resulting in a small peak on the force-displacement curve during the plateau phase.

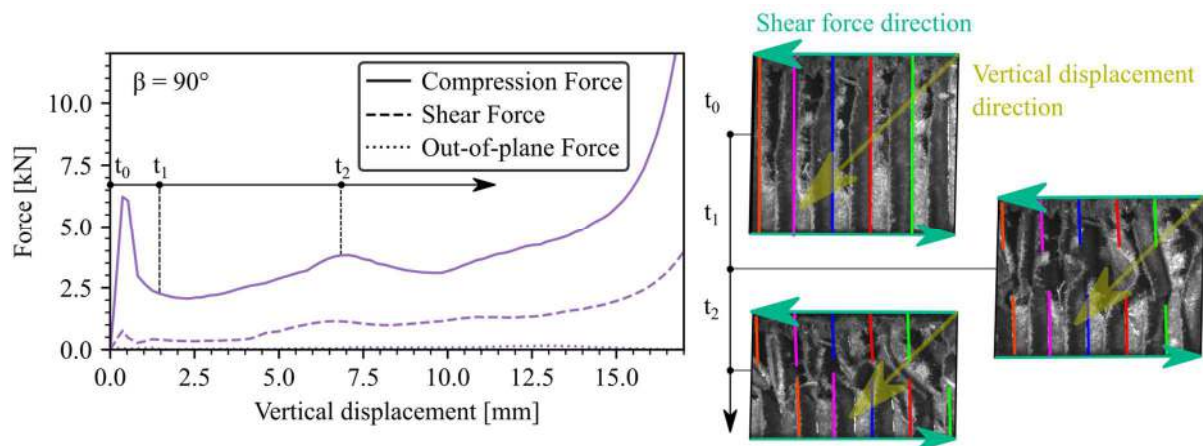


Fig. 7 – Focus on the force-displacement curve oscillation phenomenon.

Note that the more the β increase, the more this phenomenon is visible on the specimen force-displacement curves. This can be explained by the lack of displacement control between the upper and lower skin on the out-of-plane direction (OP) which allows the skins to slightly move on the direction of the weaker in-plane shear direction W during the plateau phase. For the $\beta=90^\circ$ configuration, the weaker shear direction W is aligned with the shear direction force which explain that this oscillation phenomenon is more visible on this configuration than on the others.

CONCLUSION

In order to characterize a Nomex® core material glued to its skins under quasi-static combined shear-compression loading, a new experimental device has been designed. This apparatus relies on a triaxial load cell placed under the tested specimen in order to extract the compression, out-of-plane and shear components independently. A special care is paid for the homogeneity of the specimen loading, the relative measurement of the upper and lower skin displacements and the inertial coupling during acceleration phase under dynamic solicitation. A dedicated finite element model of the developed device was developed. It has demonstrated the ability of the device to provide reliable measured physical quantities. Moreover, the associated post-processing method was able to provide accurate estimations of the mechanical characteristics of the behavior of the tested material. Based on this apparatus, a quasi-static experimental campaign was conducted on hexagonal Nomex® honeycomb core of thickness 15 mm, core 3.17 mm and density 48 kg.m^{-3} . This campaign highlighted the dependency of the mechanical behavior of this material to the in-plane shear orientation β under combined shear-compression solicitation. Indeed, the observations show that the mechanical strength of the tested Nomex honeycomb is stable for $\beta \leq 22.5^\circ$ and start to decrease once this stage is reached. Finally, the oscillation phenomenon observed in the force-displacement curves has been physically explained.

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