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Experimental and numerical analysis of the shear nonlinear behaviour of Nomex honeycomb core: Application to insert sizing

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ABSTRACT

This work is a contribution to the understanding of the nonlinear shear behaviour caused by cell postbuckling in Nomex honeycomb cores. First, an experimental benchmark study was made of different designs for the shear testing of honeycomb cores. Then, several test specimens were fabricated and tested, a 3D DIC system being used to measure and record the displacements. An Artificial Neural Network (ANN) was also used to identify the onset of bucking and collapse of the cells. The influence of the overall boundary conditions of shear tests on the buckling of the cells is presented both experimentally and numerically. The reversibility and test procedure results suggest that it may be possible to allow the shear strength to be increased by up to 35% under certain conditions.

1. Introduction

Sandwich structures are widely used for applications in a variety of domains, such as the aerospace, naval, civil, and automotive fields, for acclimated transportation, aircraft parts, fluid storage, embedded electronics, etc.

These structures offer exceptional benefits when they are used in aeronautics. The incorporation of this technology into aircraft structures has proved to provide an excellent solution to mass reduction problems thanks to the resulting high bending stiffness and low weight, which allows lightweight parts to be designed. Nevertheless, as far as primary structures are concerned, honeycomb cores have so far been restricted to helicopter structures and to some business jets [1–3] but they are widely used for secondary structures in civil aviation. Most of the core used, e.g. for cabin interiors or landing gear doors, is made of Nomex honeycomb [4–7]. It is well known that, when a sandwich is subjected to a bending load, the core absorbs almost all the shear components of the force. Consequently, the shear properties of the core are very important for the sandwich design. Nevertheless, these properties are not as simple to determine as it may seem because the honeycomb core is a cellular structure and not a solid material.

Various tests are available for obtaining the shear properties of a honeycomb core, such as three and four point beam flexure (ASTM C393), double- and single-lap shear tests (the latter is normalized in the ASTM C273 [8]), or variants such as the method for testing thick honeycomb composites developed by NASA. However, the rail shear test is the most commonly used method. Such tests should provide very similar responses for the elastic characteristics of a given core. Nevertheless, the response may be affected by the thickness of the core and correcting factors need to be applied [9–11].

There have been several investigations of the nonlinear behavior of honeycomb cores. In the related literature, the main topic is clearly the compressive response, a phenomenon that has been studied for a long time (see McFarland since 1965 [12] or Wierzbicki [13]). Many authors have studied the compressive behavior - mainly to analyse the energy absorbing capabilities of honeycomb ([12–17] for example) or, more precisely, the crush behavior of the core after a low-velocity/low-energy impact on a sandwich [17–24]. Today, the tendency is to use very refined finite element analysis with explicit code to model the complex failure mode following crushing of the Nomex Honeycomb core.

However, by understanding the structural behavior of the hexagonal cell and by making an analogy with the postbuckling of stiffened structures [22], it is possible to propose simplified discrete models that are very accurate [22–24].

There are far fewer studies concerning the nonlinear behavior of honeycomb in shear. In 1992, Zhang and Ashby [25] stated that “The linear-elastic regime terminates when the cell walls of the honeycombs buckle elastically or bend plastically, or fracture in a brittle manner” but, for low density honeycombs as in the case of Nomex, it is the buckling that explains the nonlinear response. Zhang and Ashby then developed an analytical model based on the buckling formulas of the plates, which allowed shear collapse stress to be calculated but did not investigate the nonlinear domain itself. They also underlined the experimental difficulties related to the fact that it is impossible to test

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honeycomb alone in pure shear. Pan et al. [26,27] analysed the shear buckling of aluminium honeycombs and proposed improved analytical methods for calculating the buckling load. Bianchi et al. [28] analysed the nonlinear responses of honeycomb made of aluminium in shear experiments and proposed finite element modelling with initial imperfections. The analysis also focused on their behavior in the orthotropic or off-axis directions. The model makes it possible to correctly predict the stiffnesses and the critical buckling load, which is considered here, as in previous publications, as the sizing load. Gornet et al. [29] analysed nonlinear shear behavior using a symmetrical shear test, but proposed a nonlinear model based on damage mechanics only in compression.

In fact, there are also studies on the nonlinear shear behavior of honeycombs by authors interested in the pull-out of inserts in sandwich structures [4], and this is also what motivated the present study. Bunyawanichakul et al. [5,6] propose a nonlinear model of highly loaded inserts that take the nonlinear honeycomb response, the nonlinear potting behaviour and the punching failure of the CFRP laminate skins into account. The nonlinear shear laws (τ vs γ) are obtained by a 3-point bending test and identification with a finite element model. Roy et al. [30], like Heimbs [31], model the exact geometry of the honeycomb to find nonlinear shear responses. However, the results depend on good determination of the material characteristics of the impregnated aramid paper used [32] and on whether the local geometry is properly taken into account. Seemann and Krause [4] have proposed a very detailed model of Nomex honeycomb that exhaustively considers the honeycomb defects and mesostructure and is able to model the nonlinear shear response with a rail shear test.

To sum up, the research effort on nonlinear shear behaviour of honeycomb remains limited and some results are questionable. For example, it can be seen that the buckling modes that occur during a rail shear test and those in proximity to inserts are very different, although the core is subjected to shear in both cases (Fig. 1). In particular, for the two parts of Fig. 1, the vertical cell edges remain straight near the insert whereas they buckle for the rail shear test. This means that the two honeycomb cores may show different structural behaviour and thus different failure scenarios. Similarly, the nonlinear shear behavior varies according to the authors; for example, the differences between the results obtained by Bunywanichakul et al. [5,6] and by Seeman and Krause [4] deserve to be explained. Finally, although many authors identify the shear buckling of honeycomb cells perfectly, no author has raised the question of the reversibility of postbuckling to date. Yet postbuckling is the basis for the design of aeronautical structures [33–35] that tolerate its reversibility without their strength being affected. Therefore, it would be possible, a priori, to consider not the critical buckling load but a non-reversible postbuckling threshold as the design load.

The present study reports a detailed experimental and numerical investigation of Nomex honeycomb core buckling and postbuckling under different boundary conditions through different types of tests.

2. Experimental study of the shear behaviour of HRH-78 under conventional boundary conditions

First, a benchmark study was made of the designs of specimens for the shear testing of honeycomb cores. Then, 12 specimens were tested, the tests being recorded by a 3D digital image correlation system (DIC). The data obtained were analysed to study the buckling of the cells. Finally, a detailed description was made of the nonlinear behaviour and buckling evolution of the cells.

2.1. Benchmark of specimen designs for shear testing of honeycomb cores

In this work, four different types of specimens were fabricated and tested to observe the advantages offered by each design for a study of the nonlinear shear properties of a honeycomb core. The aim was to select the most appropriate design for obtaining the curves of average shear stress vs. engineering shear strain (denoted by γ) under cyclic loading, and determining the shear modulus of the core and the shear strength of the core. The tests also had to allow us to observe the evolution of the nonlinear behaviour of the structure itself and the evolution of buckling in it, and, finally, had to give repeatable results. The double rail shear test described in ASTM C273 [8] was excluded from this study because of its inability to permit proper cyclic tests after buckling of the cells.

2.1.1. Benchmark test specimens: description

The specimens were fabricated using 20 mm thick HRH-78-3/16-3.0 Nomex honeycomb core. According to the manufacturer [37], the shear moduli were 24.13 MPa and 31.71 MPa for the W and L directions respectively. The shear strengths, using the correction factor given by the manufacturer, were 0.513 MPa and 0.785 MPa for the W and L directions respectively. For this first analysis, only one of each kind of specimen was made.

The first specimen to be tested, and thereafter used as a reference, was a sandwich beam in a three-point test (Fig. 2). This specimen was identical to those used by Bunyawanichakul et al. [5,6] to investigate the shear properties of the HRH-78 Nomex honeycomb core. Also, this type of testing was performed by Giglio et al. in Ref. [38]. When a load is applied to this kind of sandwich beam, the core is subjected almost entirely to shear stresses as the skins absorb the flexural components. Therefore, tests of this type are very often used to determine the shear properties of honeycomb cores [39]. The core was oriented in the L direction and the skins where made of aluminium that was 2 mm thick. The specimens were 20 mm wide × 20 mm high × 160 mm long and the distance between the supports was 140 mm.

A double lap specimen (Fig. 3-a) was made and tested. As for the previous specimen, the core was subjected to shear stress while the flexural forces were dissipated by the symmetry of the specimen. The core was oriented in the W direction, the skins where made of 5 mm thick aluminium and each specimen was 15 complete cells long.

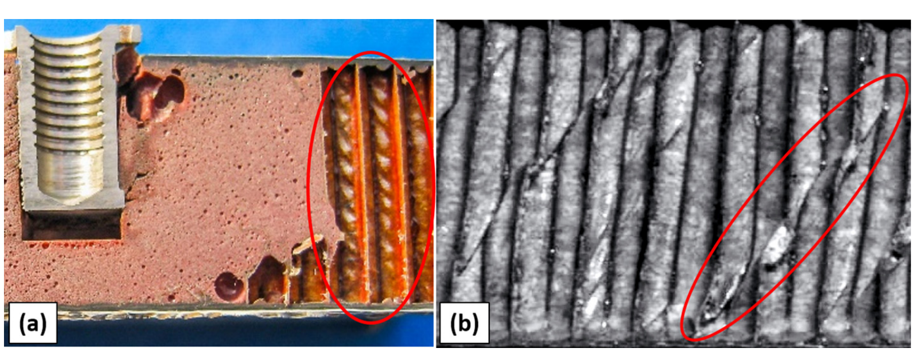

Fig. 1. Comparison of the buckling pattern of two Nomex honeycomb cores subjected to shear loads: (a) an insert specimen after a pull-out test where the cells have plasticized (extracted from Ref. [36]), versus (b) a single rail shear test (reproduced from Seemann et al. [4]).