Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Mechanical Response of Aluminum and Nomex Honeycomb Sandwich Panels under Localized Quasi-Static Indentation

Boubekeur Mohammed Bilel Mertani[1], Boualem Keskes[1], Adel Chouiter[1,2], Abderrahmane Bentouhami[1].
[1] *Laboratoire de Mécanique de Précision Appliqué (LMPA), Institut d'Optique et de Mécanique de Précision (IOMP), Université Sétif 1 Ferhat Abbas, 19000, Sétif, Algérie.*
[2] *Institut des Sciences et des Techniques Appliquées (ISTA), Université Constantine 1 Frères Mentouri, 25000, Constantine, Algérie.*

ARTICLE INFO

Received: 28 Feb 2025

Revised: 15 Apr 2025

Accepted: 05 May 2025

ABSTRACT

This study investigates the buckling behavior of composite honeycomb sandwich panels subjected to quasi-static indentation through a combined experimental, analytical, and numerical approach. Sandwich panels with aluminium (AHC) and Nomex (NHC) cores were tested under various indenter geometries (cylindrical, conical, truncated cone, and hemispherical) and different cell sizes (3.2 mm, 6.4 mm, and 9.6 mm). The influence of core material, cell size, and indenter geometry on critical buckling load, failure modes, and energy absorption was systematically evaluated.

A theoretical model was developed to predict the threshold buckling load based on geometric and material parameters, and validated against experimental results. Finite element simulations using ABAQUS provided insight into damage evolution and agreed closely with both theoretical predictions and experimental measurements.

The results show that smaller cell sizes and higher core densities improve indentation resistance and delay buckling. Indenter geometry significantly affects both the failure mode and the extent of damage. These findings contribute to a better understanding of the mechanical behavior of lightweight sandwich structures under localized loading and provide design guidelines for improving their structural performance in aerospace and transportation applications.

Keywords: Aluminum honeycomb sandwich, Nomex, Buckling, Quasi-static indentation, Light-weight structures.

INTRODUCTION

Due to advantages of light weight, high stiffness and strength ration, design flexibility, etc, honeycomb sandwich structures are attractive structural components and are therefore widely used in aerospace, ship building, automobile, civil engineering and other sectors. The mechanical properties of these structures can be influenced by loading and service conditions. In order to explore the mechanical behaviors of honeycomb sandwich structures, especially to investigate indentation and impact behavior and reveal different failure modes, also to evaluate the macro structural performance, some research works were carried out such as compression, three-point bending, four-point bending, impact and quasi-static indentation were experimental investigated in detail. The results show that the mechanical properties are sensitively influenced by geometries of specimen, cell size, face-sheets and core material, indenter geometry, mid span length distance, impact energy loading, velocity and so on [1-9].

Williamson and Lagace [10] performed the experiments to study static indentation and impact behavior of composite sandwich plates. They gauged the face-sheet deflection under the indenter and also studied the core and face-sheet damages with varying core thickness and laminate layup. They found that the load-deflection characteristics and failure predictions of sandwich plates under static indentation and low velocity impact tests were similar. Herup and Palazotto [11] performed the low-velocity impact and static indentation tests on sandwich plates composed of 4 to 48-plies graphite/epoxy cross-ply laminate face-sheets and Nomex honeycomb cores to characterize the damage initiation as a function of face-sheet thickness and loading rate. Turk and HooFatt [12] derived the closed-form solutions for the deformation and fracture responses of a composite sandwich plate subjected to static indentation of

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

a hemispherical-nose indenter. The composite sandwich was modeled as an infinite orthotropic, elastic plate resting on a rigid-plastic foundation. They assumed that the face-sheet deflection is several times the laminate thickness, so that the bending moments may be neglected and only the membrane forces are considered in the face-sheet. They also derived an approximate solution for the load indentation response of the considered composite sandwich plates. Anderson and Madenci [13] investigated the force indentation response of sandwich panels subjected to a rigid spherical indenter. The considered sandwich panels were made of graphite/epoxy face sheets with a polymethacrylimide foam core. They developed a three-dimensional analytical solution method to determine the complete stress and displacement fields in the sandwich panel, as well as the contact pressure arising from static indentation by the rigid sphere. Ruan et al. [14] experimentally investigated the mechanical response and energy absorption of aluminum foam sandwich panels subjected to quasi-static indentation loads. The considered sandwich panels consisted of two aluminum face sheets and a closed cell aluminum foam core. They studied the effects of face-sheet thickness, core thickness, and boundary conditions, adhesive and surface condition of face-sheets on the mechanical response and energy absorption of sandwich panels. Hosseini et al. [15] studied the static indentation response of a composite sandwich plate subjected to a flat-ended cylindrical indenter. The sandwich plate was rigidly supported, which prevented the global deformation and allowed only local deformation for the sandwich plate. They assumed that the top face-sheet deformations to be several times its thickness so that the top face-sheet was considered as a membrane and the bending effects were neglected. To simplify the analysis, they also neglected the in-plane displacement components u and v of the top face-sheet, compared to its transverse deflection w.

However, sandwich panels are known to be susceptible to impact damage by foreign objects that are expected during the life of the structure. Impact induced damage can cause drastic decrease in the strength of the structure. Impact may come from a variety of causes. Typically, low-velocity impact may result from tool drops, hail and debris thrown up from runways [16]. Visual inspection may reveal little damage, but significant damage may occur between the impacted face-sheet and the core [17]. Reduction of structural stiffness and strength can occur and, consequently, propagate under further loading. This relatively poor resistance to localized impact loading has become a concern for both manufacturers and end-users that need to locate damages for repair of structural members. Widespread application of sandwich structures in aircraft industries has thus been inhibited due to the lack of understanding of the impact damage mechanisms, and the effect of such damage on structural performance [18] .

V. Crupi et al [19, 20] analyzed the static and low-velocity impact response of two typologies of aluminium honeycomb sandwich structures with different cell size. The static bending tests produced various collapse modes for panels with the same nominal size, depending on the support span distance and on the honeycomb cell size. Simplified collapse models were applied to explain the experimental observations and a good agreement between predicted and experimental limit loads was achieved. Low-velocity impact tests were, also, performed on the two typologies of aluminium honeycomb sandwiches and a theoretical approach, based on the energy balance model, has been applied to investigate their impact behaviour. The failure mode and damage of the honeycomb panels have been investigated using the 3D Computed Tomography.

By carrying out quasi-static localized indentation tests, the mechanical properties and energy absorption capacity of the integrated sandwich panel of aluminum foam and epoxy resin with different immersed resin thickness, boundary conditions and indenter type were studied. It was also compared with traditional aluminum foam sandwich panel. The experiments indicated that with the increase of immersed resin thickness, the specimen's energy absorption capacity and yield load increase significantly; in the condition of fully fixed, energy absorption capacity and yield load of specimens are higher than the condition of simply supported, which have been greatly improved compared to the traditional sandwich panel; elastic modulus of specimen under cylindrical indenter is higher than specimen under square indenter, but the elastic modulus in the yield and destruction phase are highly similar to each other. The specimens maintain good stability under indentation, no peeling-off or cracking happens between the composite layer and core [21]. Ashab et al [22] have detailed the first extensive study of the dynamic out-of-plane indentation of aluminum honeycombs at a range of different loading velocities. Dynamic and quasi-static mechanical properties of honeycombs were comparatively analyzed to investigate the strain rate effect on both mean plateau stress and energy absorption. Indentation and compression tests of three types of HEXCEL 5052-H39 aluminum hexagonal honeycombs were tested using MTS and high speed INSTRON machines at strain rates from 10-3 to 10-2 s-1 respectively. The tearing energy was calculated as the difference in energy dissipated in indentation and compression of the same type of honeycomb. It was found that tearing energy was affected by strain rate and nominal density of honeycomb. Empirical formulae were proposed for tearing energy in terms of strain rate.V. Crupi et al [23] analyzed of the bending and the low - velocity impact response of aluminum foam sandwiches reinforced by the outer skins made of glass fiber reinforced epoxy matrix. The results were compared with those obtained for aluminum foam sandwiches without glass fiber skins. Also, an analytical model for the peak load prediction under low velocity impact was developed and the predicted values are in good agreement with the experimental measurements. The impact response of the sandwiches was investigated using a theoretical approach, based on the energy balance model and the model parameters were obtained by the tomographic analyses of the impacted panels. This combined experimental and theoretical investigation has particular importance for applications that require lightweight composite structures with a high capacity of energy dissipation, such as the transport industry, where problems of collision and crash have increased in the last years.

It was observed that the load-indentation curve showed a linear behavior for low values of indentation, followed by a non-linear regime with a quick decrease in the sandwich panel stiffness caused by the extensive foam core crushing in the area under the indenter. Indenter geometry has great influence on the indentation and impact resistance of sandwich panels, which has been shown, for example, in Wen et al. [24] where quasi-static indentation into sandwich panels with PVC foam core and GFRP face sheets was studied using hemi-spherical, flat and conical indenters. Zhou et al. [25] investigated the quasi-static indentation of sandwich panels with aluminum honeycomb core and CFRP face sheets using hemi-spherical and flat indenters, and showed that the failure mechanisms depend on the indenter nose shape. Most investigations about the effect of the nose shape on the quasi-static response of sandwich panels were limited to flat and hemi-spherical indenters. S. Nurashikin and AkilHazizan [26] investigated the low-velocity impact response of thermoplastic honeycomb core sandwich structure with aluminum skin by conducting drop-weight impact tests. At first, the shear modulus of the thermoplastic honeycomb core and flexural modulus of the skin were investigated through a series of flexural test. Later in the study, the indentation test was conducted to the specimen in order to investigate the indentation characteristic. It was found that the indentation characteristic of this sandwich structure can be analyzed using a Meyer indentation law. The impact response of the thermoplastic honeycomb core sandwich structures was predicted using a simple energy-balance model which meant for energy absorption in bending, shear and contact effects. In addition, the energy-balance model was also used to identify the energy partitioning during the impact event. The results were show that the energy absorption profile was relatively constant over the range of impact energies, suggesting that the fraction of energies does not vary with impact conditions [27].

Muscat-Fenech and al [28], they tested using the default hemisphere indenter also included other standard rock geometries conical, square-based pyramid and flat-faced cylindrical on marine structures. In their study, the damage incurred under each variation of indentation impact was described, in terms of force, absorbed energy and indentation displacement. New contact laws have been suggested for the different rock geometries. Destructive sectioning of the panels provides the visual damage incurred through the thin face skins and core and the roles played by all members comprising the sandwich panels.

In this contribution, buckling of AHC and NHC composite sandwich panel subject to quasi-static indentation was investigated. The effects of indenter geometry, core material and honeycomb core's cell size have been investigated. The indentation resistance depends on these keys parameters and is strongly influenced by the cell diameter and by the core material for the honeycomb. In meantime, ABAQUS program is used to numerically calculate the corresponding critical buckling loads. In other hand, a three-dimensional (3D) reconstruction of the honeycomb panels has been carried out in order to acquire exactly the dimension and the shape of the damage (buckling). In addition, an analytical model for the threshold load prediction under indentation conditions was developed and the predicted values are in good agreement with the experimental measurements.

THEORETICAL APPROACH

To be effective under intense impulsive loads, a sandwich structure must be able to dissipate in core crushing a significant fraction of the kinetic energy initially acquired. Consequently, if a sandwich structure is to retain its integrity with only limited crushing, its core must have ample crushing strength and energy-absorbing capacity.

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Our work will be described the buckling which occurs in indented honeycomb sandwich panels and the honeycomb mechanics needed to evaluate the failure loads for buckling.

It has been proved that the buckling of the honeycomb sandwich panel is one of the most frequent failure forms [2, 19-21, 29-31].

- Quasi-static indentation loading:

Based on the cells' collapse mechanisms of the hexagonal honeycombs revealed from the experimental results under the quasi-static loading, an analytical model is established to deduce the threshold buckling load of the honeycomb as functions of indenter geometry, cell size, and the mechanical properties of the base material.

The buckling load, F, at indentation distance, z, will be comprised of a component due to the honeycomb core and, for sandwich specimens, a component due to the facings, that is:

$$F^{In\ buck} = {F_{cI}}^{In\ buck} + F_I^{shear} \quad (1)$$

When a sandwich panel is subjected to transverse loading, it is widely accepted that the displacement of indenter is the sum of the indentation of top face-sheet and the global bending deflection [30-36]. All damages occurring in the experimental results are found to initiate in localized region (Figure 1) This means that the damage initiation is independent on the boundary condition while dependent on the radius of indenter, dimensions in transverse direction of the specimen, cells size, mechanical properties of the face-sheets and the core.

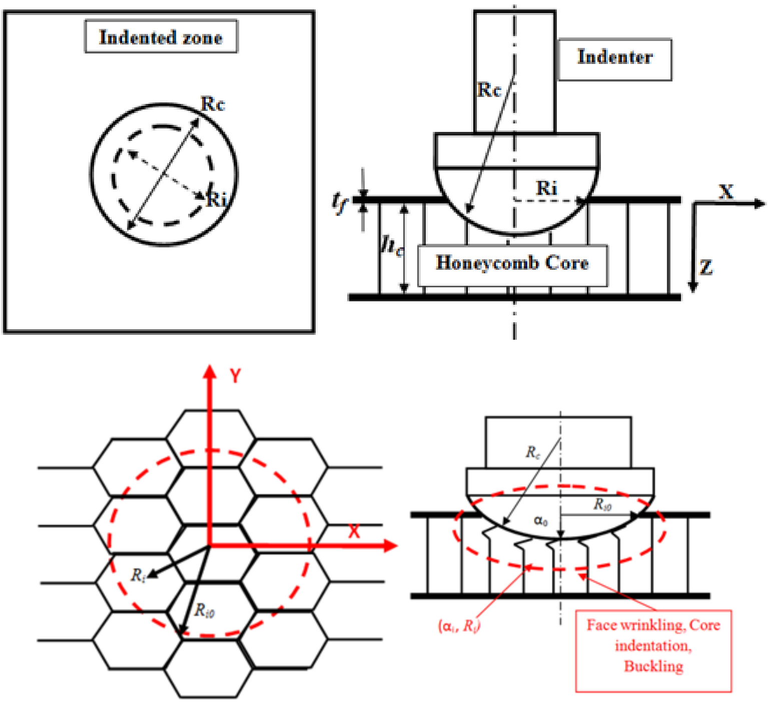

Figure1: Parameters and geometrical configuration of indentation problem.

In this study two assumptions are used:

- External loading is taken mainly by the cells wall of the honeycomb structure.
- The contact between honeycomb and indenter is assumed to be perfect which means that the honeycomb in contact with the indenter follows the indenter shape during crushing.

The computation steps (for a spherical indenter case) are as follows:

1. Computation of polar radius (Ri).

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Since the cells walls positions are regular, their distance is a function of the diameter of the honeycomb cell used. At the beginning, the indenter is considered to be in the center of the first cell to be touched to facilitate the computation by regarding only the quarter.

2. Computation of the damaged surface radius (Ri) when indenter crushes down to α0.

   The value R0 is calculated as a function of α and Re (indenter radius) by using the following equation:

   $$R_e = \sqrt{\alpha_0(1 - 2R_i)} (2)$$

3. Computation of the penetration of each vertical edge (αi).

   The penetration of vertical edges inside the damaged surface (R_e<R_i) is calculated using the following equation:

   $$\alpha_i = \sqrt{R_i^2 - {R_e}^2} - R_i + \alpha \ (3)$$

4. Computation of the reaction force (${F_c}^{buckling}$).

   Knowing the penetration of each cell wall (αi) obtained by the experimental results, the reaction force for each cell wall (${F_{ci}}^{buckling}$) is obtained by:

   $$F = \sum F_{\cdot ci}{}^{buckling} \ (4)$$

5. Computation of indentation force.

   It is the sum of the reaction force of cell wall:

To have a complete indentation law, the same step is computed for several increments α0 of indentation.

Shear stress in the top face-sheet is highly concentrated in the localized area of contact (Figure 2) The limit load Fshear is given as [35, 37]:

$$F_I^{shear} = 2\pi R_e t_f \tau_f \ (5)$$

Where tf is the thickness of the face-sheets and Reis the contact radius:

$$R_e = \sqrt{\alpha(2R_i - \alpha)} \ (6)$$

And the indentation is given as:

$$\alpha = F\ \beta \ (7)$$

Where β is given by

$$\beta = \frac{1}{\sqrt{\frac{D_f E_c}{h_c}}} (8)$$

Where Ec and hc are the Young modulus and thickness of the core respectively. The symbol Df is the effective bending rigidity of face sheet. Substituting Eq. (6) and (7) into Eq. (5), the limit load for shear damage of the top face can be derived as:

$$F_I^{shear} = \pi^2 \beta R_i \left(t_f \tau_f\right)^2 \ (9)$$

As can been seen in Eq. (9), limit load F_I^{shear} is a function of the radius of indenter$R_i$and thickness face t_f, and the through thickness modulus of the core h_c.

Results obtained from the quasi-static tests showed that the indentation failure of the sandwich panel is mainly dependent on core materials, cell size and indenter geometry [30-36]. Core buckling is widely reported as the first damage mode that occurs in experiments Figure 2.

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

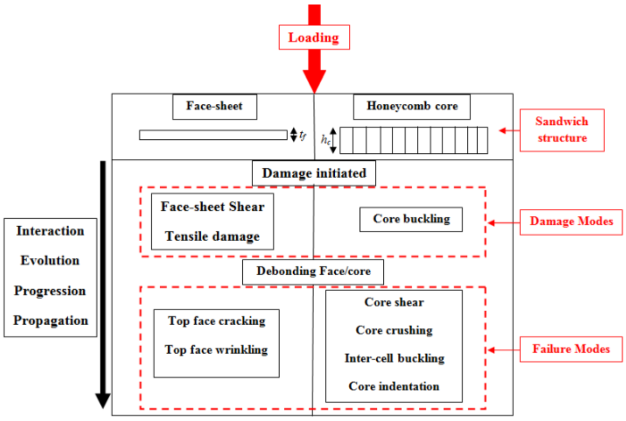

Figure 2: Failure process in sandwiches structures under indentation loading.

Since honeycomb core is made of hexagonal interlinked thin walls, this damage mode will be the dominant mode for large core thickness of hc. For this sandwich panel, the threshold load has been developed:

$$F_{cI}{}^{In\ buck} = \sigma_c^s K_c A_f \ (10)$$

$$A_f = \pi\alpha(2R_i - \alpha) \ \ (11)$$

$$F_c{}^{In\ buck} = \sigma_c^s K_c \pi\alpha(2R_i - \alpha) \ (12)$$

The value of Kc was determined empirically from the experimental data and was found to be 2 for the investigated sandwiches.

The number of the damaged cells can be obtained simply by the ratio between Af and the cell size.

The limit load of Eq. (12) is independent of indenter radius while experimental results show that the radius Ri may affect the limit load for core buckling.

The analysis of Eqs. (9) and (12) concludes that as the face-sheet thickness increases, the limit loads for both modes will also increase. This means increasing the face-sheet thickness will significantly increase the ultimate load. Likewise, increasing the core density will definitely leads to higher compressive strength.

Figure 3 shows a typical failure process following the quasi-static indentation tests. The honeycomb structures failed by the progressive cell buckling mechanism that is characteristic of honeycombs. However, the buckling of the cells towards the periphery of the damage zone is not uniaxial due to the curved geometry of the indenter. The facings either failed by plastic deformation and eventual shearing or by plastic deformation and eventual debonding and wrinkling.

MATERIALS AND METHODS

MATERIALS

Composite sandwich plates consist of aluminum (AHC) and Nomex (NHC) core and a pure aluminum face sheet (Figure 3) were used in this study. The honeycomb core is an open cell with varying a size of 3.2, 6.4 and 9.6 mm. The specimen preparation and testing were in accordance with ASTM standards. Each plate is measured 50x50x10 mm, with a core thickness of 8.8mm and a thickness of 0.6 mm for each top and bottom face-sheet. Detailed characteristics of the composite sandwich components are reported in Tables 1 and 2.

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

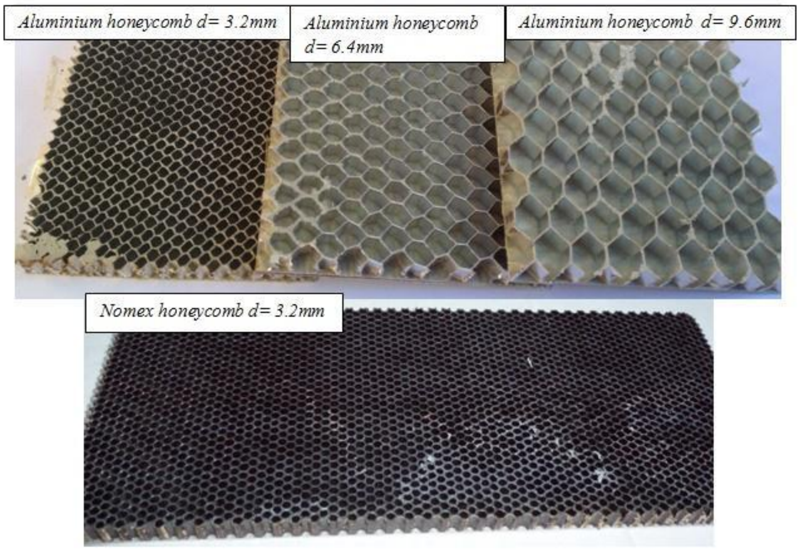

Figure 3: Typologies of investigated sandwiches.

Table 1: Material properties for AHC and NHC tested.

Typology	Density (kg/m3)	σyc (MPa)	τyc(MPa)	d (mm)	hc (mm)	tc(mm)
AHC	130	3.4	0.9	3.2	8.8	0.06
AHC	82	2.5	0.6	6.4	8.8	0.08
AHC	55	0.9	0.6	9.6	8.8	0.08
NHC	128	3,10	1,16	3.2	8.8	0.076

Table 2: The facesheet materials.

Young modulus[Gpa]	Shear strength [Mpa]	σyf [Mpa]	Density[kg/m3]	Poisson ratio	tf(mm)
70	268	165	2700	0,33	1

METHODS

Two types of honeycomb panels were investigated under quasi-static indentation condition for their different stiffness and energy absorption ability: Nomex honeycomb sandwiches (NHS) and aluminum honeycomb sandwiches (AHS) using a different steel indenters: Cylindrical, conical, hemispherical and truncated cone shown in Figure 4.Three different AHS typologies have been investigated: the first one consists of hexagonal cells with diameter of 3.2 mm (AHS, d = 3.2 mm, hc= 8.8 mm and tc = 0.06 mm) and has a honeycomb density equal to about 130 kg/m3, the second one has hexagonal cells with diameter of 6.4 mm (AHS, d = 6.4 mm hc= 8.8 mm and tc = 0.08 mm) and has a honeycomb density equal to about 81 kg/m3. The NHS panels have hexagonal cells with diameter of 3.2 mm (NHS, d = 3.2 mm, hc= 8.8 mm and tc = 0.076 mm) and core density of 128 kg/m3. The skins of all the investigated panels are made of aluminum and bonded to the core by an epoxy adhesive (chemical composition: C 72.12%, O 27.71%, Cl 0.17%). The skin thickness tf is about 0.6 mm. More details of these honeycomb materials are given in Tables 1 and 2. The overall dimension of the sandwich panel is 50×50×10mm.

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

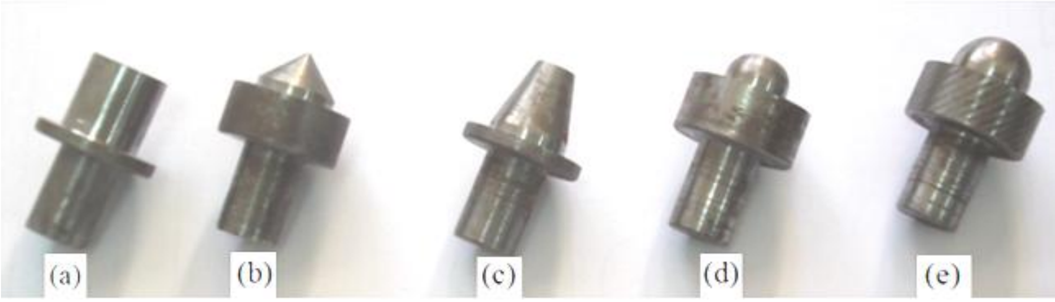

Figure 4: The different indenters' geometry used in this study: (a) Cylindrical, (b) Conical, (c) Truncated cone, (d) Hemispherical 16mm and (e) Hemispherical 20mm.

Mechanical testing was realized by employing a universal testing machine model by Zwick/Roell Instruments equipped with a 100 KN load cell (Figure 5) at room temperature (25°C). For each test, the load-indentation characteristic was recorded. The indentation loading was controlled by displacement at a constant cross-head speed of 2 mm/min. For each test, the load versus indenter displacement data is collected via a digital data acquisition system.

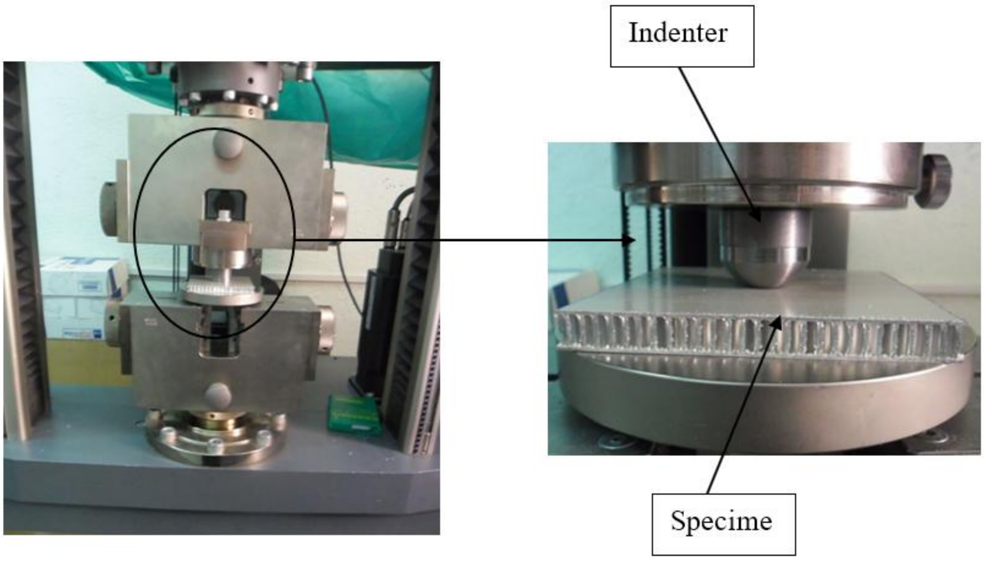

Figure 5: Quasi-Static experiment machine.

RESULTS AND DISCUSSIONS

A typical load-indentation curve obtained from quasi-static indentation tests on AHS panel and hemispherical indenter (HS Ri = 20 mm) is shown in Fig.6. From this figure it was observed that the load-indentation curve showed a linear behavior for low values of indentation, followed by a non-linear regime with a quick decrease in the sandwich panel stiffness caused by the extensive cells core buckling in the indented area. It was seen that there are two main peaks on the load-indentation curve (see figure 6), the first peak mostly relates to penetration of the upper face-sheet and between the first and second peak, damage relates mostly to the crushing of the core with cell buckling.

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

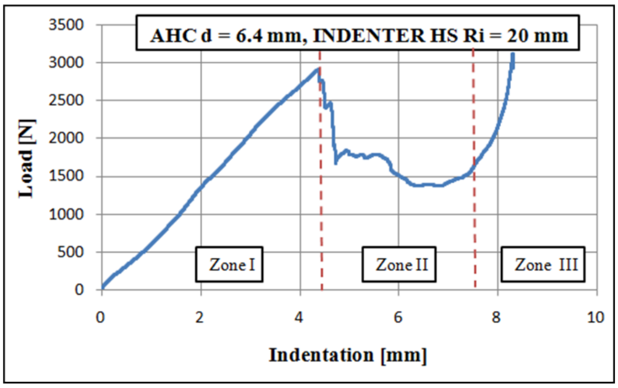

Figure 6: Load-indention curve of AHC d = 6.4 mm with Hemispherical indenter (Ri = 20 mm).

All the panels with different cell size and core materials present similar behavior, but the deformation between upper and lower face-sheet failure increases as the cell size increases. Also, for the threes holds buckling loads which are different for sandwich panels with different cell size, core materials and indenter geometry. It was found that the indentation load increases with the decreases of the cell size of the core and it is increased when the diameter of the indenter increases. From the results, it is apparent that the indentation load and the damage for a composite sandwich panel under quasi-static indentation test are dependent on the cell size, the indenter geometry and the core materials. These effects are discussed in detail as follows.

Similar tests have been already conducted by [19, 20, 28, 29] and the experimental results showed that the indentation resistance depends on the indenter geometry, cells size and core's material.

The deformation of the face-sheet of the honeycomb sandwich panels occurred mainly by cracking, wrinkling and bending while deformation of the core was by progressive buckling [16-23].

Damage in composite sandwich structures subjected to indentation load obviously depends on many factors, including face-sheet and core properties, cell size, and indenter geometry. For a given specimen type, four basic response/failure modes can be identified as the level of indentation increases: elastic recoverable deformation, local deformation/ indentation, face-sheet cracking and wrinkling, and core crushing and buckling. For low levels of indentation load, the structure deforms globally within the elastic range without permanent deformation. For higher load levels, local deformation appears due to core crushing followed by local bending and shearing of the upper face-sheet. For even higher load levels, but below the penetration threshold, additional failure modes have been identified including extensive core indentation/cracking, face-sheet cracking, delamination within the face-sheet, and debonding between the face-sheet and core.

The experimental values of the critical load Fexp were compared to the value predicted by the developed theoretical approach (paragraph 2) using eq. (1).

Table 3 reports the experimental and predicted critical loads and their comparison.

Table 3: Comparison of FEA, Experimental and Theoretical data for indentation loading.

Cell size	Ri [mm]	α [mm]	αnum [mm]	Fexp[N]	Fth[N]	Error %	Fnum[N]	Error %
NHS (d=3.2mm)	20	4	-	4500	4717	4.8	-	-
AHS (d=6.4mm)	20	4.3	4.1	2914	2891	1	3022	3.7
AHS (d=3.2mm	20	4.9	-	3426	3706	8.1	-	-

- Effect of the indenter geometry

Figure 7 shows for each indenter the load-indentation data for the same cell size (AHC 3.2mm) and core material. Noticeable differences in the mechanical behavior of sandwich samples under quasi-static indentation load are

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

evidenced at varying indenter geometry and the cell size. In Figure 8 it is possible to observe how the threshold loads increase at increasing contact area between the indenter and specimen.

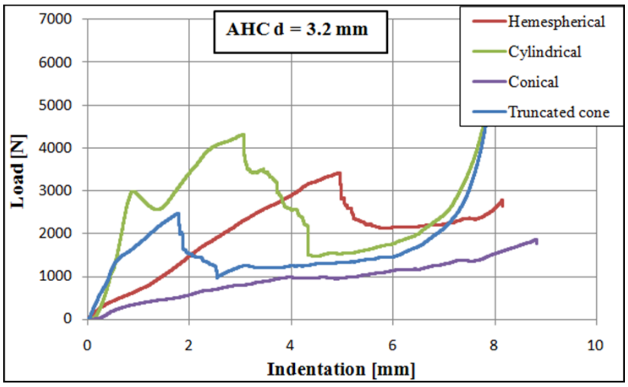

Figure 7: Effect of indenter geometry on indentation behavior (AHC d = 3.2 mm).

Reporting three hold loads, as dictated by this standard has no significant meaning for such an indenter. The load will keep on increasing so long as the advancing cross-sectional area increases.

Figures 8 show the damage inflicted for the different types of indenters on the same composite sandwich panel type. Albeit there are notable differences in the type of damage inflicted by each indenter (see Figure 9). The indenters (a) and (e) both produced a larger area of cracking than the indenter (b). Also; it was seen that there are similarities in the indentation failure processes in case of indenters (a) and (c).

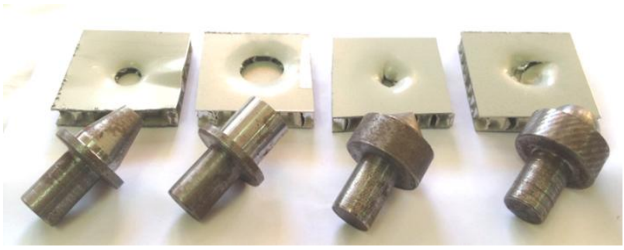

Figure 8: Failure modes of indentation test for each indenter.

The indenter geometry influences the shape of the damaged area on the sandwich as shown in Figure 9 In fact, failure can be radial for the indenter (b), a crack starts at the indenter/material interface with a petals shape during the penetration, or it can be circumferential for the indenters (a), (c) and (d, e), the material under the indenter undergoes compressive stress and the strain interests the whole sample [17]. However, there is a notable difference in the total energy absorbed for the using indenters (see Figure 7). It is notable that under these loading conditions, the specimen stiffness is higher with the indenters (a) and (c) than is the case for the indenters (b) and (d), this phenomenon is due to the contact geometry effects.

It is noticed in Figures 7, 8 and 9 that the geometry of the indenter has significant influence on the stiffness of the composite sandwich panels and the buckling process.

The maximum indentation buckling load was observed for indenter with diameter of 20mm (see Figure 11).

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

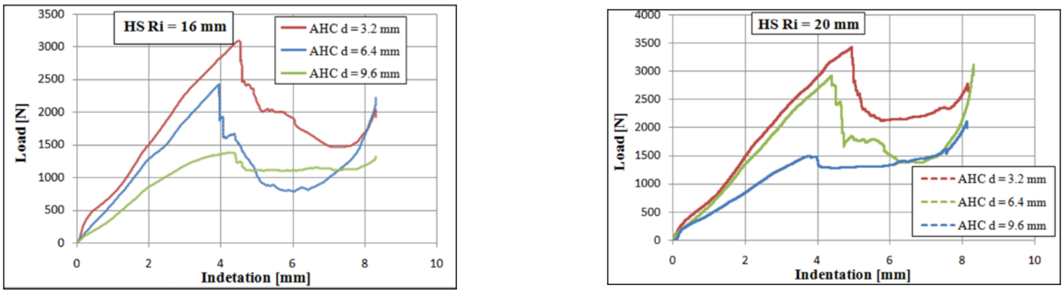

Figure 9: Effect of indenter diameter on indentation behavior at varying cell size: a) HSRi = 16 mm and b) HS Ri= 20 mm.

From the obtained results, indenter geometry has great influence on the indentation resistance and the failure mechanisms of composite sandwich panels.

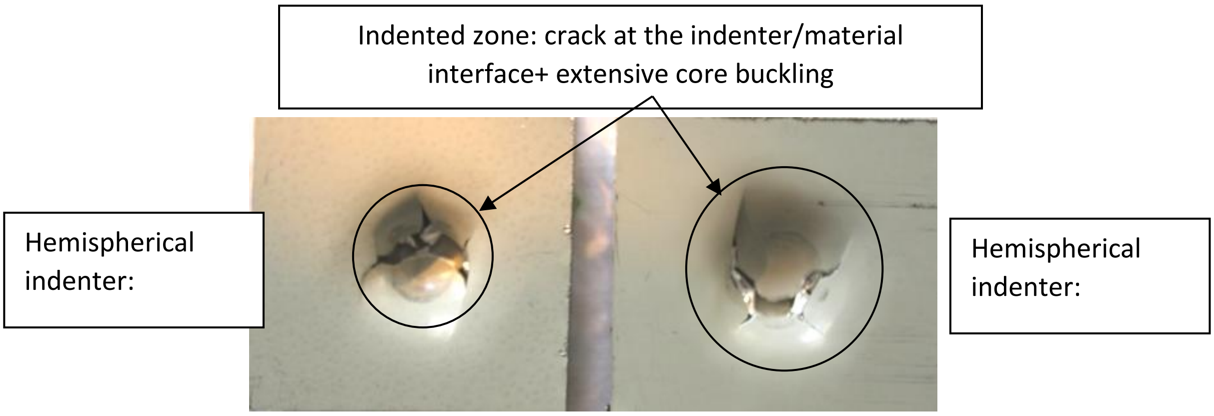

Figure 10: Obtained Failures Modes for an aluminum honeycomb sandwich with cell size of 9.6mm.

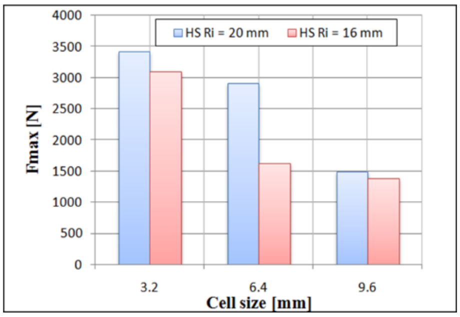

Figure 11: Obtained Failures Modes for an aluminum honeycomb sandwich with cell size of 9.6mm.

- Effect of the cell size of honeycomb core

To study the effect of the cell size on indentation behavior several tests were carried on AHS panel with different cell sizes (3.2, 6.4 and 9.6 mm). Figures 13 show load-indentation curves using cylindrical, hemispherical and conical indenter, respectively.

Good repeatability was observed for identical sandwich panels in terms of their load–indentation behavior. Two general observations can be made from Figs13, i.e., for the same indentation displacement, the indentation resistance decreases with the increase of the cell size. The first observation can be explained by the fact that the stiffness of the sandwich panel increases with the increase of the density of the core [28]. Also, the cell size induces relevant effects on the mechanical performances of the samples under static indentation load. This is evident from the results shown in Figures 14 that compares the max indentation load at varying the cell size for each indenter. It was found that the indentation load increases with the decreasing of the cell size of the core. Damaged area decreases with the increase of density since the effect of the indentation becomes local due to the increase of stiffness of the panel [19-26, 28].

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Figures 13 also indicate that the absorbed energy at failure depends on the cell size; there is an increase of absorbed energy when the core cell size is decreased from 9.6 to 3.2 mm; however, when the core cell size is decreased, there is a reduction in the absorbed energy of the structure. This behavior is observed for all indenters.

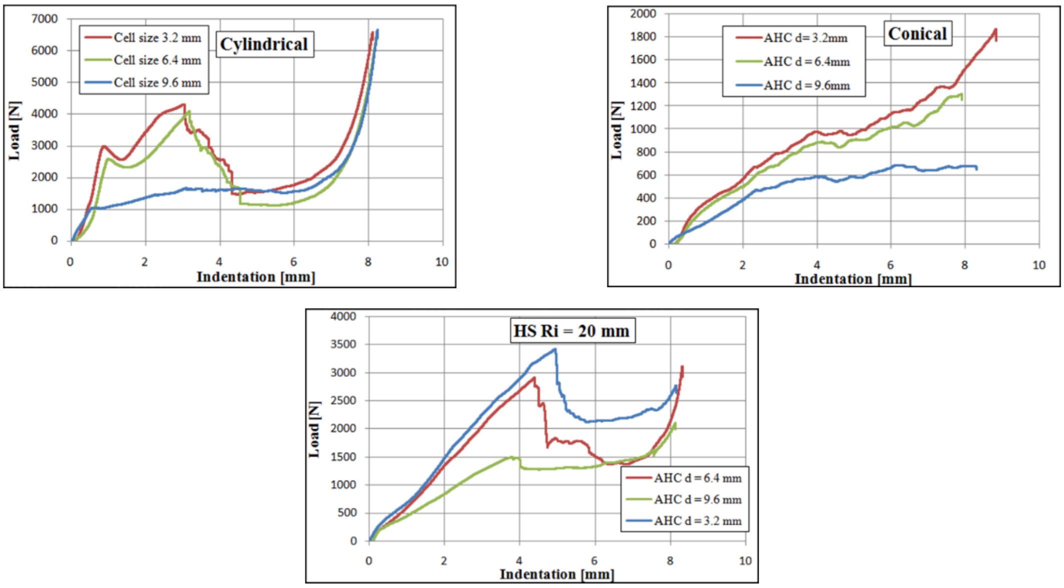

Figure 12: Effect of cell size on indentation behavior: a) conical b) hemispherical and c) cylindrical indenter

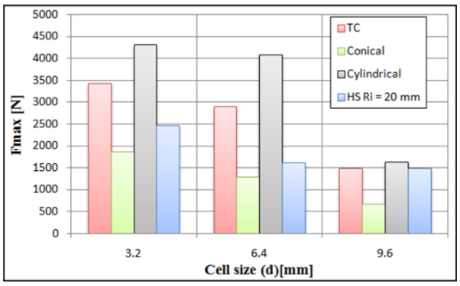

Figure 13: Max indentation load at varying the cell size for each indenter.

- Effect of the core materials

The effect of core material on indentation load is illustrated in Figures 14, which reveal load-indentation data for each indenter at same cell size. The reported tests were performed with NHC and AHC core; the conclusions drawn from such results are valid also for the test obtained with different values of indenter geometry, as it is possible to observe from the data summarized in Figures 15. For a sample with NHC the typical behavior is observed, as the one shown in Figures 14. On the converse, if the core is made of AHC the load/indentation curves do not present the small drops, but a unique collapse. For the all indenters, there is considerable difference in the load-indentation curves for the NHC and AHC. From the same Figure 15 it is possible to compare the indentation resistance of the two kind of core; the NHC samples show almost a higher indentation load resistance values compared to the one exhibited from the AHC samples. Figure 15 shows the max indentation loads for the same cell size for the both used core material.

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

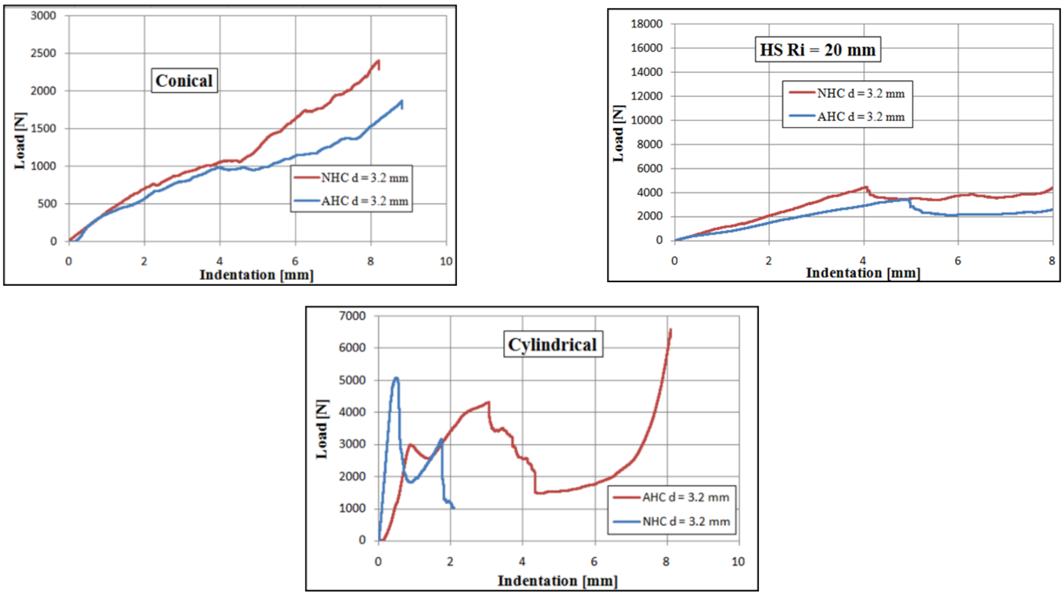

Figure 14: Effect of core material on indentation behavior of honeycomb sandwich: a) hemispherical indenter, b) cylindrical indenter and c) conical indenter

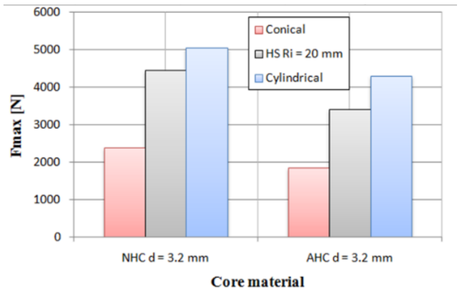

Figure 15: Max indentation load at varying core material for each indenter.

- Failure modes

Besides the indentation strength, the establishment of the incurred failure modes during the experiment is also important. As the load increased, initial honeycomb wall buckling and later regional cell wall folding and core crushing were observed in the AHC core sandwich panels (Figures 16). The failure modes of NHC panels under indentation load show similar behavior as that of AHC honeycombs. But at NHC core panels, which are much brittle than AHC, prior to core crushing failure, crack generation incurred (Figure 15). The failure, started as a cell wall buckling, caused cracks at greater indentation loads.

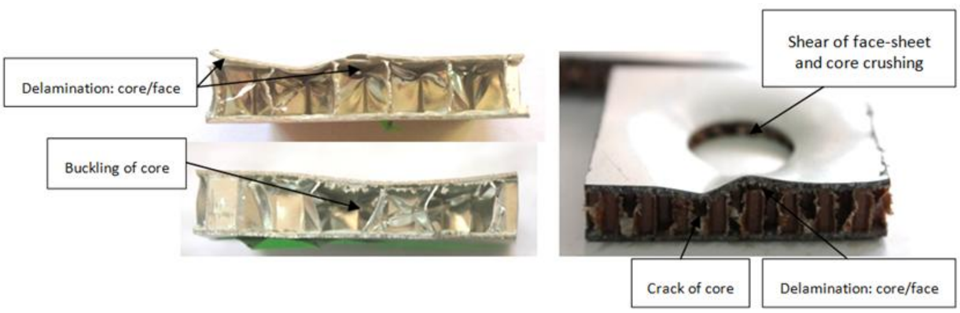

Figure 16: Obtained failures modes.

Damage in composite sandwich structures subjected to indentation load obviously depends on many factors, including face-sheet and core properties, cell size, and indenter geometry. For a given specimen type, four basic

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

response/failure modes can be identified as the level of indentation increases: elastic recoverable deformation, local deformation/ indentation, face-sheet delamination and/or debonding from the core, and core buckling. For low levels of indentation load, the structure deforms globally within the elastic range without permanent deformation. For higher load levels, local deformation appears due to core crushing followed by local bending and shearing of the upper face-sheet. The specimen undergoes permanent deformation without face-sheet failure. For even higher load levels, but below the penetration threshold, additional failure modes have been identified including extensive core indentation/cracking, face-sheet buckling, delamination within the face-sheet, and debonding between the face-sheet and core. Typical failure modes are shown in (Figures 17 and 18).

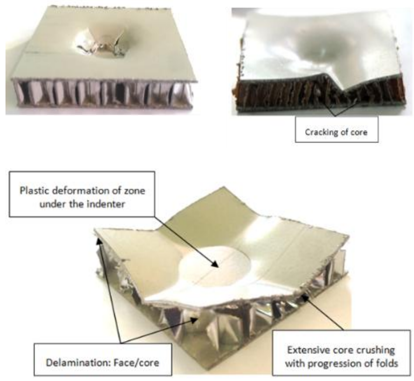

Figure 17: typical failure modes observed during indentation: core crushing and failure of face.

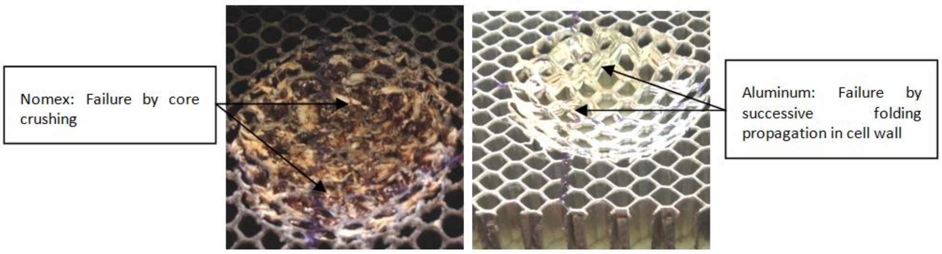

Figure 18: difference between failure modes

NUMERICAL MODELING

In this work, a three-dimensional geometrically correct finite element model of the honeycomb sandwich plate and a rigid indenter was developed using the commercial software, ABAQUS (figure 19). This discrete modeling approach enabled further understanding of the parameters affecting the initiation and propagation of indentation damage. The top and bottom face-sheets, as well as the honeycomb sandwich core, were meshed with shell elements.

The intender was modeled as a rigid body using four-nodded linear tetrahedron continuum elements, and its motion was governed by the rigid body reference node. In addition, gravitational load and an initial velocity, v0, were assigned to the indenter at its reference node. The indenter was also constrained to move only in the out-of plane direction (i.e. Z-direction) of the plate. To reduce the run time, all simulations commenced with the indenter situated just 0.1 mm above the sandwich plate.

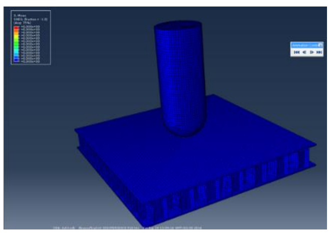

Figure 19: Correct finite element model of the honeycomb sandwich plate and a rigid indenter

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Figure 21 reports the numerical load curve for an Aluminum honeycomb. It has cell size of 6.4 mm and cell wall thickness of 0.8mm. The analysis is carried out applying quasi static load in the thickness direction on a 100*100 mm2 plate. In agreement to what expected, the curve shows an initial linear elastic and stiff response, then, once reached the maximum value of the force, the curve presents a sharp drop due to the beginning of the vertical edge deformation (buckling of core). During this phase the force reaches a plateau, and finally the diagram shows the condensation phase. Otherwise, the maximum deflection (α) of the panel is given by figure 22.

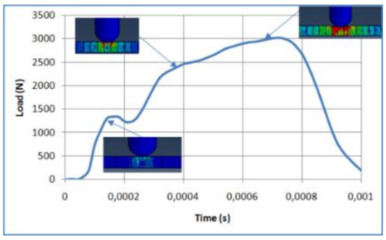

Figure 20: Numerical crushing behavior of an aluminum honeycomb panel with d=6.4 mm.

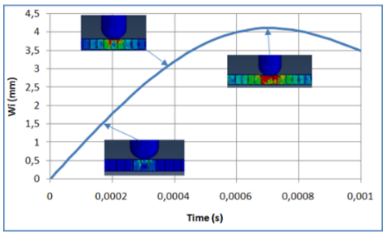

Figure 21: Max numerical indentation Wi of an aluminum honeycomb panel with d=6.4 mm.

Figure 22 shows the details of indentation behavior of AHC d = 6.4 mm at different stages of simulation.

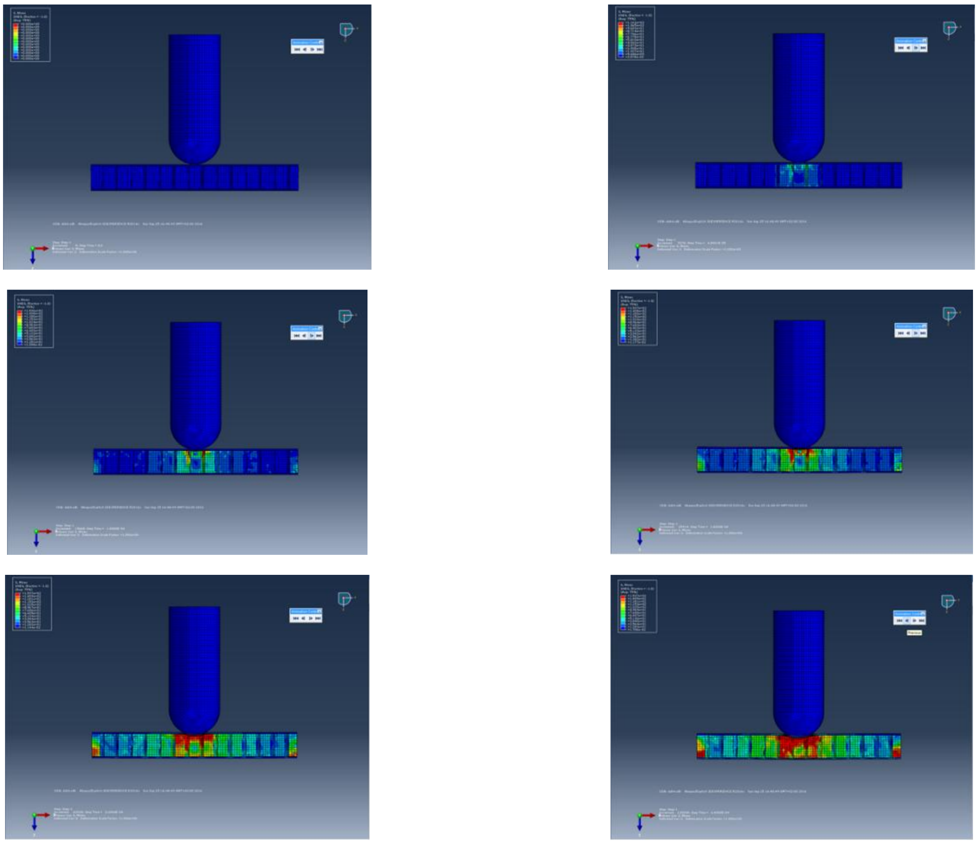

Figure 22: Detailed numerical damage shape at different indenter displacements (AHC d=6.4)

Journal of Information Systems Engineering and Management
2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

- Comparison of experimental, theoretical and finite element analysis results

The comparison of experimental, theoretical and numerical buckling load of AHC with different cell sizes subjected to quasi-static indentation loading with hemispherical indenter is discussed in the following section. The experimental values of the critical load Fexp were compared to the value predicted by the developed theoretical approach (paragraph 2.1) using eq. (12) and numerical value obtained with ABAQUS (paragraph 5.1).

As a first step, an attempt was made to validate the theoretical model with experimental results. A comparison of experimental and theoretical predicted data of AHC and NHC for different core cell's size (AHS 6.4, 3.2 mm and NHC 3.2 mm) is given in Figure 23. This figure shows peak load using a hemispherical indenter with a diameter of 20 mm. The indentation resistance decreases with increasing the cell size. This can be explained by the fact that the stiffness of the sandwich panel increases with the increase of the density of the core [19-22]. Also, the cell size induces relevant effects on the mechanical performances of the samples under static indentation load.

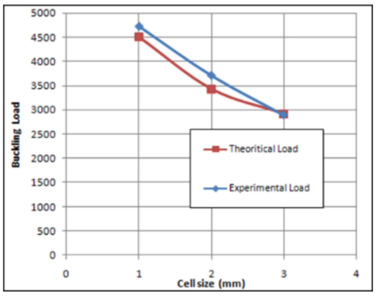

Figure 23: Comparison of buckling peak load obtained from theoretical approach and quasi-static indentation test (AHS 6.4, 3.2 mm and NHS 3.2 mm).

In meantime, the numerical model which has been developed in section 5 was used to derive the critical buckling load only in case of the aluminum sandwich core AHC d = 6.4 mm. Table 3 reports all the results and it depicts the peak load of buckling for the different used cell's size for two materials.

Results were compared with test data, as well as simulation results. The comparisons indicate that a good agreement existed between the experimental and predicted results, in terms of peak load and overall profile. As can be seen, numerical results behave in accordance with experiments (Figures 24 and 25). As for the honeycomb core the numerical results are in good agreement with the experimental ones.

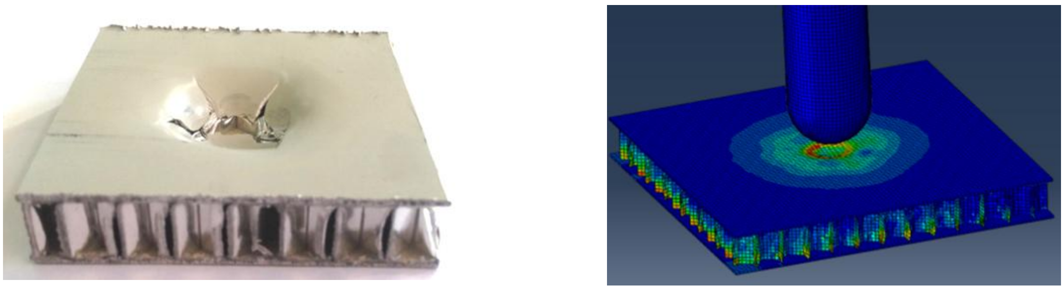

Figure 24: Comparison of failure modes observed during indentation: (a) experimental and (b) finite element results.

CONCLUSIONS

The indentation failure behavior of honeycomb core sandwich panels is studied by examining the effects of core, cell size and indenter geometry on indentation load. From the experimental results it is possible to draw out the following considerations:

- It was observed that the load-indentation curve showed a linear behavior for low values of indentation, followed by a non-linear regime with a quick decrease in the sandwich panel stiffness caused by the extensive core crushing in the area under the indenter.

- The failure mechanisms during indentation mechanisms depend on the indenter geometry. Damaged area depends strongly on the indenter geometry. The largest damaged areas were observed for cylindrical and hemi-spherical indenters while the smallest damaged areas were observed for conical indenters. The indenter geometry influences the shape of the damaged area on the sandwich. In fact, failure can be radial for a conical indenter (a crack starts at the pin/material interface with a petals shape during the penetration) or it can be circumferential if the indenter is cylindrical/ spherical (the material under the pin undergoes compressive stress and the strain interests the whole sample) [17].
- From the obtained results, indenter geometry has great influence on the indentation resistance and the failure mechanisms of composite sandwich panels.
- It was found that both indenter geometry and core density have large influence on the indentation response of the sandwich panels. Several failure modes for the studied sandwich panels were identified including face failure, core failure and skin/core debonding.
- The load is increased when the diameter of the indenter increases.
- It was found that the indentation load increases with the decrease of the cell size of the core.
- Damaged area decreases with the increase of density since the effect of the indentation becomes local due to the increase of stiffness of the panel.
- The stiffness of the sandwich panel increases with the increase of the density of the core. Also, the cell size induces relevant effects on the mechanical performances of the samples under static indentation load.
- The sandwich with high core density is much suitable for working conditions in which localized load resistance is necessary.
- There is an increase of absorbed energy when the core cell size is decreased from 9.6 to 3.2 mm; however, when the core cell size is decreased, there is a reduction in the absorbed energy of the structure.

The Nomex samples show almost a higher indentation load resistance values compared to the one exhibited from the aluminum core samples.

REFRENCES

[1] S. Abrate, Impact on Composite Structures. Cambridge: Cambridge University Press, 1998.
[2] A. T. Nettles and M. J. Douglas, "A comparison of quasi-static testing to low velocity impact testing," in Composites Materials: Testing, Design, and Acceptance Criteria, ASTM STP 1416, A. Zureick and A. T. Nettles Eds. West Conshohocken, PA: American Society for Testing and Materials International, 2002, pp. 116-130.
[3] E. A. Flores-Johnson and Q. M. Li, "Experimental study of the indentation of sandwich panels with carbon fibre-reinforced polymer facesheets and polymeric foam core," Composites Part B: Engineering, vol. 42, no. 5, pp. 1212-1219, 2011, doi: 10.1016/j.compositesb.2011.02.013.
[4] C. C. Foo, G. B. Chai, and L. K. Seah, "Quasi-static and low-velocity impact failure of aluminium honeycomb sandwich panels," Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, vol. 220, no. 2, pp. 79-89, 2006, doi: 10.1243/14644207jmda98.
[5] J. Y. Lee, K. B. Shin, and J. C. Jeong, "Experimental and Numerical Simulation Studies of Low-Velocity Impact Responses on Sandwich Panels for a BIMODAL Tram," Advanced Composite Materials, vol. 18, no. 1, pp. 1-20, 2009, doi: 10.1163/156855108x385311.
[6] E. Lolive and J. M. Berthelot, "Non-linear behaviour of foam cores and sandwich materials, part 2: indentation and three-point bending," Journal of Sandwich Structures & Materials, vol. 4, no. 4, pp. 297-352, 2002.
[7] J. Pach, R. Wróblewski, and B. Muszyński, "Comparative Analysis of Sandwich Composites with Balsa, Rohacell®, and Nomex® Cores for Aerospace Applications," Materials, vol. 18, no. 5, p. 1126, 2025. [Online]. Available: https://www.mdpi.com/1996-1944/18/5/1126.

[8] Y.-n. Zhang, Y. Tian, X.-y. Liu, H. Zhou, J. Zhou, and Y.-b. Hu, "Quasi-static indentation responses of FMLs/2.5 D woven carbon-fiber honeycomb sandwich structures under different structural parameters," Thin-Walled Structures, vol. 198, p. 111702, 2024.
[9] A. Djellab et al., "Experimental and numerical investigation of impact behavior in honeycomb sandwich composites," Proceedings of the Institution of Mechanical Engineers, Part L, vol. 238, no. 7, pp. 1342-1357, 2024, doi: 10.1177/14644207231223638.
[10] J. E. Williamson and P. A. Lagace, "Response mechanism in the impact of graphite/epoxy honeycomb sandwich panels," in Proceedings of the Eighth ASC Technical Conference, 1993.
[11] E. J. Herup and A. N. Palazotto, "Low-velocity impact damage initiation in graphite/epoxy/nomex honeycomb-sandwich plates," Composites Science and Technology, vol. 57, no. 12, pp. 1581-1598, 1997.
[12] M. H. Turk and M. S. Hoo Fatt, "Localized damage response of composite sandwich plates," Composites Part B: Engineering, vol. 30, no. 2, pp. 157-165, 1999.
[13] T. Anderson and E. Madenci, "Graphite/epoxy foam sandwich panels under quasistatic indentation," Engineering Fracture Mechanics, vol. 67, no. 4, pp. 329-344, 2000.
[14] D. Ruan, G. Lu, and Y. C. Wong, "Quasi-static indentation tests on aluminium foam sandwich panels," Composite Structures, vol. 92, no. 9, pp. 2039-2046, 2010.
[15] S. M. R. Khalili, M. Hosseini, K. Malekzadeh Fard, and S. H. Forooghy, "Static indentation response of an in-plane prestressed composite sandwich plate subjected to a rigid blunted indenter," Journal of Sandwich Structures and Materials, vol. 15, no. 1, pp. 59-69, 2013.
[16] B. Castanié, C. Bouvet, Y. Aminanda, J. J. Barrau, and P. Thévénc, "Modelling of low-energy/low velocity impact on Nomex honeycomb sandwich structures with metallic skins," International Journal of Impact Engineering, vol. 35, no. 7, pp. 620-634, 2008.
[17] C. Borsellino, L. Calabrese, and G. Di Bella, "Windsurf-Board Sandwich Panels Under Static Indentation," Applied Composite Materials, vol. 15, no. 2, pp. 75-86, 2008, doi: 10.1007/s10443-008-9058-2.
[18] Y. Li, A. Xue, and Y. Xia, "Comparison with Low-Velocity Impact and Quasi-static Indentation Testing of Foam Core Sandwich Composites," International Journal of Applied Physics and Mathematics, vol. 2, no. 1, pp. 58-62, 2012.
[19] V. Crupi, G. Epasto, and E. Guglielmino, "Collapse modes in aluminium honeycomb sandwich panels under bending and impact loading," International Journal of Impact Engineering, vol. 43, pp. 6-15, 2012.
[20] V. Crupi, G. Epasto, and E. Guglielmino, "Comparison of aluminium sandwiches for light-weight ship structures: Honeycomb vs. foam," Marine Structures, vol. 30, pp. 74-96, 2013.
[21] S. L. Cheng, X. Y. Zhao, Y. J. Xin, S. Y. Du, and H. J. Li, "Quasi-static localized indentation tests on integrated sandwich panel of aluminum foam and epoxy resin," Composite Structures, vol. 129, pp. 157-164, 2015.
[22] A. S. M. Ashab, D. Ruan, G. Lu, S. Xu, and C. Wen, "Experimental investigation of the mechanical behavior of aluminum honeycombs under quasi-static and dynamic indentation," Materials and Design, vol. 74, pp. 138-149, 2015.
[23] V. Crupi, E. Kara, G. Epasto, E. Guglielmino, and H. Aykul, "Prediction model for the impact response of glass fibre reinforced aluminium foam sandwiches," International Journal of Impact Engineering, vol. 77, pp. 97-107, 2015, doi: 10.1016/j.ijimpeng.2014.10.005.
[24] H. M. Wen, T. Y. Reddy, S. R. Reid, and P. D. Soden, "Indentation, penetration and perforation of composite laminate and sandwich panels under quasi-static and projectile loading," Key Engineering Materials, vol. 141-143, pp. 501-552, 1998.
[25] G. Zhou, M. Hill, J. Loughlan, and N. Hookham, "Damage characteristics of composite honeycomb sandwich panels in bending under quasi-static loading," Journal of Sandwich Structures & Materials, vol. 8, no. 1, pp. 55-90, 2006.
[26] C. Y. Tan and H. Md. Akil, "Impact response of fiber metal laminate sandwich composite structure with polypropylene honeycomb core," Composites Part B: Engineering, vol. 43, no. 3, pp. 1433-1438, 2012.
[27] B. M. B. Mertani, B. Keskes, and M. Tarfaoui, "Experimental Analysis of the Crushing of Honeycomb Cores Under Compression," Journal of Materials Engineering and Performance, journal article vol. 28, no. 3, pp. 1628-1638, March 01 2019, doi: 10.1007/s11665-018-3852-2.

2025, 10(50s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

[28] C. De Marco Muscat-Fenech, J. Cortis, and C. Cassar, "Impact damage testing on composite marine sandwich panels, part 1: Quasi-static indentation," Journal of Sandwich Structures and Materials, vol. 16, no. 4, pp. 341-376, 2014.

[29] V. Crupi, G. Epasto, E. Guglielmino, H. Mozafari, and S. Najafian, "Computed tomography-based reconstruction and finite element modelling of honeycomb sandwiches under low-velocity impacts," Journal of Sandwich Structures & Materials, vol. 16, no. 4, pp. 377-397, 2014.

[30] P. R. Jeyakrishnan, K. S. K. K. Chockalingam, and R. Narayanasamy, "Studies on buckling behavior of honeycomb sandwich panel," The International Journal of Advanced Manufacturing Technology, vol. 65, no. 5-8, pp. 803-815, 2013.

[31] M. O. Kaman, M. Y. Solmaz, and K. Turan, "Experimental and Numerical Analysis of Critical Buckling Load of Honeycomb Sandwich Panels," Journal of Composite Materials, vol. 44, no. 26, pp. 3087-3100, 2010, doi: 10.1177/0021998310371541.

[32] X. Fan, I. Verpoest, and D. Vandepitte, "Finite Element Analysis of Out-of-plane Compressive Properties of Thermoplastic Honeycomb," Journal of Sandwich Structures and Materials, vol. 8, no. 5, pp. 437-458, 2006, doi: 10.1177/1099636206065862.

[33] Z. Li, Z. Zheng, and J. Yu, "Low-velocity perforation behavior of composite sandwich panels with aluminum foam core," Journal of Sandwich Structures and Materials, vol. 15, no. 1, pp. 92-109, 2013.

[34] S. Nurashikin and H. Akil, "Preparation and properties of thermoplastic honeycomb core sandwich structure with aluminum skin," Journal of Composite Materials, vol. 46, no. 2, pp. 183-191, 2012, doi: 10.1177/0021998311410996.

[35] O. T. Shitta-Bey, J. J. Carruthers, C. Soutis, and M. S. Found, "The localized low-velocity impact response of aluminium honeycombs and sandwich panels for occupant head protection: experimental characterization and analytical modeling," International Journal of Crashworthiness, vol. 12, no. 5, pp. 549-558, 2007.

[36] A. Wilbert, W. Y. Jang, S. Kyriakides, and J. F. Floccari, "Buckling and progressive crushing of laterally loaded honeycomb," International Journal of Solids and Structures, vol. 48, no. 5, pp. 803-816, 2011.

[37] S. Zhu and G. B. Chai, "Damage and failure mode maps of composite sandwich panel subjected to quasi-static indentation and low velocity impact," Composite Structures, vol. 101, pp. 204-214, 2013.