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Application of finite element analysis to honeycomb sandwich structures: a review

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ABSTRACT

Honeycomb sandwich is really one of the fundamentals to make a composite strong, stiff, very light, safe and have wonderful performance. Honeycomb materials are majorly used where high strength to weight ratio, stiffness to weight ratio is needed. Honeycomb sandwich consist of two face sheet or skin and a light core which can take many shapes, the common is hexagonal shape. The core handles shear load, while the skins resist compression and tension. This paper aims to guide the design of honeycomb sandwich structures done with finite element analysis software. The characteristic of honeycomb at microstructure and unit cell will be discussed Moreover, much demand on light weight honeycomb structures that can withstand heavy loads under different working condition are on high demand. Experimental approach can be time consuming and costly, this created room for massive research using FEA on loading response with various cores and thickness, in order to investigate the mechanical properties. This study will focus on the FEA of honeycomb sandwich done by many researches currently on commercial software's ANSYS and ABAQUS, this will be a guideline for researches to see what has been done and what is obtainable using FEA software.

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1. Introduction

Honeycomb structures are widely used in almost every part of manufacturing sector, Due to their benefits, including extremely low weight/force ratios, which leads to lower weight, lower fuel usage, According to Sorohan et al., (Alhijazi et al., 2020) composite sandwich panels are utilized in aerospace and civil infrastructures applications because of their stronger flexural/transverse shear stiffness, higher corrosion resistance, and higher flexural/transverse shear stiffness. Alhijazi et al. (Alhijazi et al., 2020) defined honeycomb as "Sheet metal or resin-impregnated sheet material (paper, fibrous glass, etc.) structured into a network of open-ended, hexagonal cells with the walls of each cell shared with its near neighbors. Sandwich constructions use honeycomb as a core.". 2000 years ago in China, the first artificial honeycomb structure was built with paper as investigated by Z. Wang (Z. Wang, 2019). The cell arrangement are mostly hexagonal in section (Y. Chen & Wang, 2022; Luo et al., 2022; Papakokkinos et al., 2022), researchers has experimented a lot of shapes on sandwich structures, circular, triangular, rectangular square or rhombic (Dutra et al., 2019; Gao et al., 2020; Ghongade et al., 2020). Honeycomb normally has a regular hexagonal geometry (the sides are equal, the angles are all 120º and the cell walls are of the same thickness) due to this, their deformations can be easily analyzed and equations of orthotropic properties is obtained by Gibson & Ashby (Gibson & Ashby, 1999). Hence, some cores can be folded, Xiang et al. (Xiang et al., 2018) used ABAQUS/Explicit to perform an analytical analysis of rectangular sandwich plates with Miura-ori folded cores. The cores used for load-bearing sandwich construction can be classified into four major classes; corrugated (Liu et al., 2022; REN et al., 2021; Torabi & Niiranen, 2021; G. dong Xu et al., 2019; Yazici et al., 2014), honeycomb(Korupolu et al., 2022; Q. Xu et al., 2021; Z. Zhang et al., 2022), balsa wood (Karaduman & Onal, 2016; H. Wang et al., 2016) and foams(Amith Kumar & Ajith Kumar, 2020; Dimassi et al., 2018; Kazemi, 2021; Laulkar et al., 2020). Figure 1 depicts the classification of sandwich core. Sandwich panels behaviors depends mainly on the geometric arrangement of core and facing materials as stated by Hussain et al. (Hussain et al., 2019). Sandwich panels are typically made up of two thin face sheets or skins and a lightweight thicker core, moreover the core is made of different materials which depends on the desired mechanical properties needed. The core material is typically a low-strength material., but its higher thickness provides the requisite high bending strength with a low overall density. In addition, the sandwich core is known for low density, high compression, stiffness and shear properties.

Manufacturing of honeycomb sandwich is majorly by corrugation, expansion and molding, while the most adopted manufacturing method is expansion and corrugation. Commonly used composite is fiber-glass, carbon fiber reinforcement plastic, Kevlar and aluminum. However, honeycombs are known to have four common types, Aluminum honeycomb, Thermoplastic honeycomb, Nomex honeycomb and stainless steel honeycomb, moreover Aluminum possess highest strength to ratio as proposed by Y. Zhang et al. (Y. Zhang et al., 2020). The strength increases exponentially relative to the core thickness while the increase in weight is negligible, and honeycomb is easily milled, routed, cut, edged, fastened and bonded, making it a first choice to reinforce any component structural area.

In addition, Fazilati & Alisadeghi (Fazilati & Alisadeghi, 2016) stated that honeycomb structures are commonly used as energy shock absorbers due to their strong characteristics and crashworthiness of high energy absorption capacity and high strength-to-weight ratio. "Mechanical property and energy absorption capability of aluminum honeycomb structures vary with impact velocity" as proposed by Z. Wang et al.(Z. Wang et al., 2014). Sandwich core of aerospace structures is often Nomex or aluminum honeycomb. Honeycomb composites are materials that are hollow-structure and therefore vulnerable to intrusion by liquid. Hu et al. (Hu et al., 2019) carried out LSTM-RNN Deep learning architecture optimized for time sequences to automatically identify common defects present in honeycomb-structured materials, which consists of debonding, adhesive pooling, and liquid ingress.

The metal composite material (MCM) is a type of sandwich formed in a continuous process by means of controlled pressure, heat and stress, from two thin metal skins attached to the plastic foundation. Hence, their classification regarding the core form and the support of the skin, it is possible to classify sandwich structures into the following groups: homogeneously supported, locally supported, regionally supported, unidirectional supported, and bidirectional supported as defined by Vijaya Ramnath et al. (Vijaya Ramnath et al., 2019)

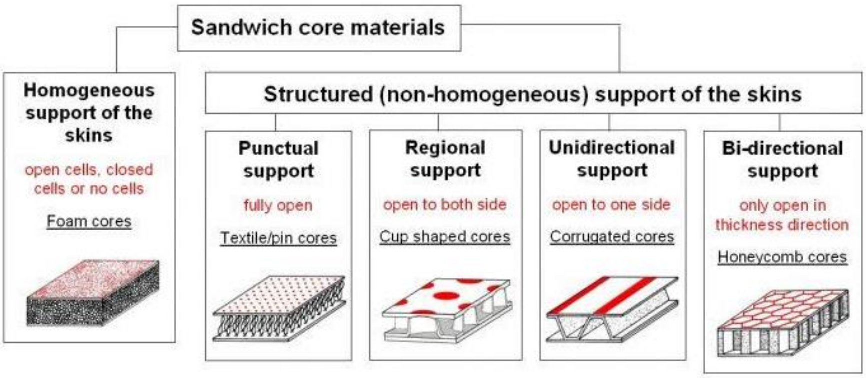


Figure 1. Classification of Sandwich core (Thomsen, 2009)

This review analyzes on the current work on honeycomb sandwich structures and application of finite element analysis to sandwich structures. Older work is only cited on the necessary basis. In this review, we focused on finite element analysis carried out on commercial software ANSYS and ABAQUS, due to vast work done in the area. Published documents from 2008 to 2021 with regards to honeycomb structures and The following FEA were obtained from the Scopus database. Figure 2 depicts a growing trend of research interest in honeycomb structures, with a focus on FEA and Figure 3 shows that China picked a lot of interest on honeycomb structures, documents published increased exponentially over the years.

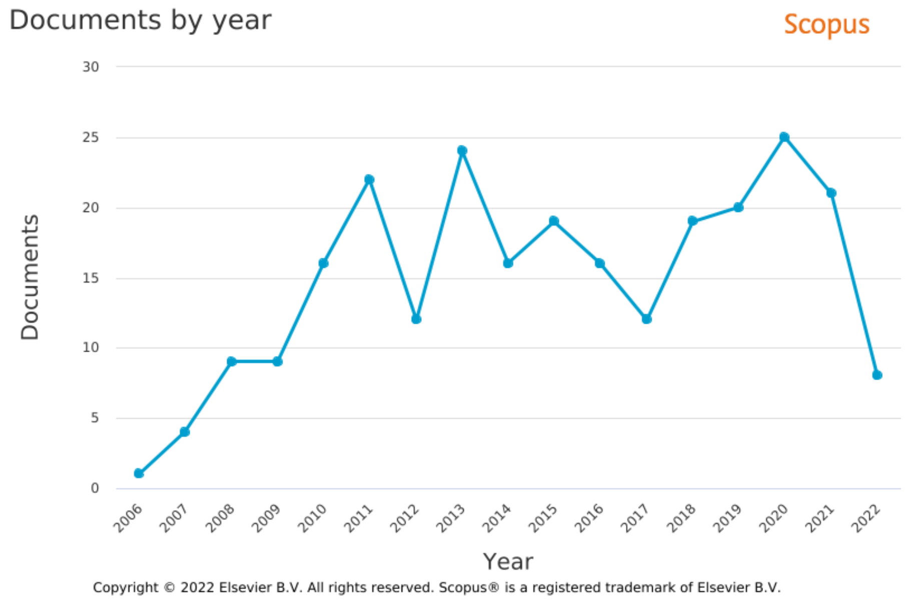


Figure 2. Published documents by country statistics from the Scopus database search keywords: (TITLE-KEY (“honeycomb structures")) AND (“FEA”) (Scopus – Sources, 03/09/2021).

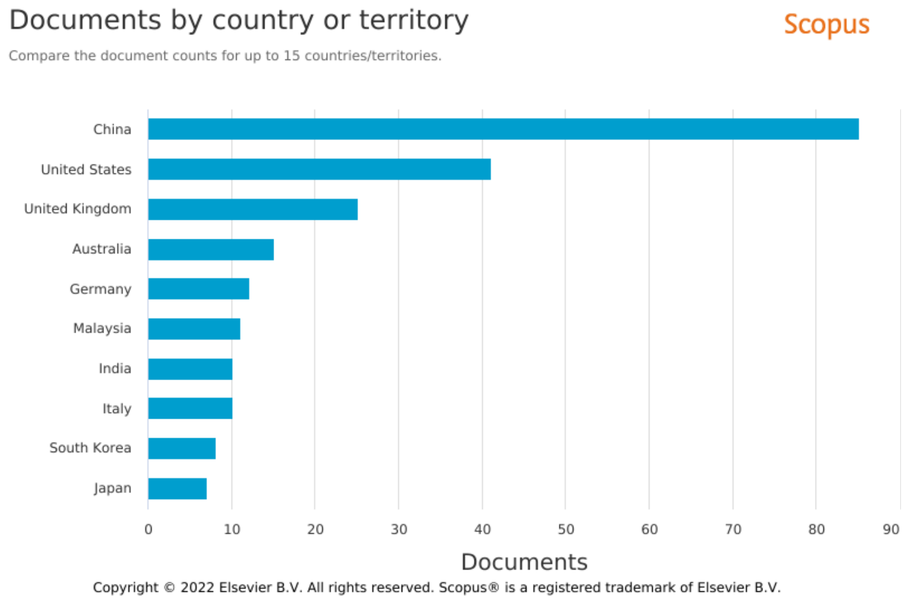


Figure 3. Published documents by country statistics from the Scopus database search keywords: (TITLE-KEY (“honeycomb structures”)) AND (“FEA”) (Scopus – Sources, 03/09/2021).

2. Analytical models

Sandwich structures are studied on the basis of a variety of theories which investigate the behavior of environmental or mechanical loading of such structures. The theories is as a result of formulation of kinematic relationships between the thickness coordinates and in-plane structures (beams or plates) or in-surface (shells) coordinates, which represents its structural displacement. The sandwich core is relatively light and the shear stiffness is negligible. In accordance, we can’t overlook transverse shear as in the case of technical theories of beams, shell and plates, that will not be applicable in most sandwich structures. In addition, the theories will be dependent on kinematic formulations for the structure's various layers.

Birman & Kardomateas (Birman & Kardomateas, 2018) stated that analytical model are used for stimulating, explaining and predictions about the mechanisms involved in complex physical process of honeycomb structures. The equations used to describe the changes in the system, Wei et al. (Wei et al., 2022) developed three-dimensional failure mechanism maps to analyze and optimize the in-plane compressive properties of all-composite honeycomb sandwich columns and analytical models were developed based on five probable failure modes: shear macro-buckling, intracellular dimpling, face wrinkling, face fracture, and debonding. Gibson & Ashby (Gibson et al., 1989) derived the most commonly used analytical expressions for sandwich flexural strength and shear rigidity. Figure 4 depicts sandwich beam schematic.

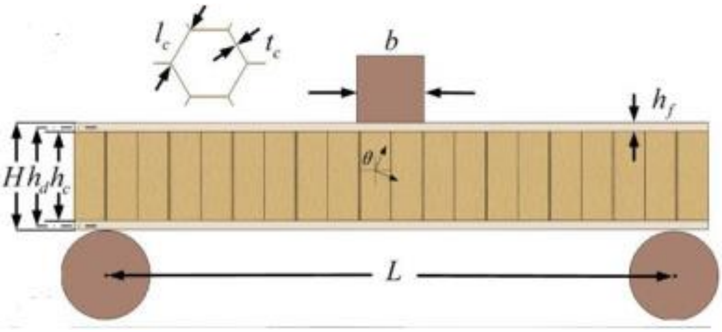


Figure 4. Sandwich beam schematic diagram under 3-point bending (Wei et al., 2020)

The sandwich flexural strength and shear rigidity is calculated by many researchers, As investigated by H G Allen (Allen, 1969), the total deflection at the mid-point of sandwich beams under 3-point bending load is shared by the face sheet bending deflections δ_B and honeycomb core shearing deformation δ_S. having the corresponding expression as:

$$\delta = \delta_B + \delta_S = \frac{FL^3}{48(EI)_{eq}} + \frac{FL}{4(QG)_{eq}} \qquad (1)$$

Sandwich beams have an equivalent flexural stiffness of $(EI)_{eq}$, and the honeycomb core's corresponding shear rigidity is $(QG)_{eq}$. The middle indenter's load is denoted by the letter F.

$$(EI)_{eq} = \frac{Ebt_f d^2}{2} + \frac{Ebt_f^3}{6} + \frac{C_{22}^H bc^3}{12} \qquad (2)$$

$$(QA)_{eq} = \frac{bd^2}{c} C_{44}^H \approx bcC_{44}^H \qquad (3)$$

Here, C_{22}^H was the core in-plane elastic modulus in the 2-direction, and C_{22}^H was the core out-of-plane shear modulus in the 2–3 direction. These two elastic constants can be calculated using the homogenization approach.

Failure of the face sheet under 3-point bending occurs due to normal stress that it carries. According to Xiong et al. (Xiong et al., 2012) the failure loads *Y* related with the failure of the skin can be evaluated using

$$Y = \frac{4h_f h_d B}{L} \cdot \sigma_f \qquad (4)$$

where *Y* is the failure strength of face sheet and *B* is the sandwich beam's width.

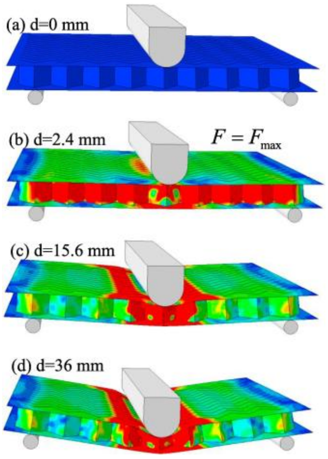


Figure 5. Sandwich Structure Deflection (Xiang et al., 2018)

Table 1. Analyzing the different properties of three configurations of sandwich panel (Xiong et al., 2012)

Property Of Sandwich Panel		1st Config.	2nd Config.	3rd Config.
Thickness of the core (c)		8mm	8mm	8mm
Face-sheet thickness (t)		0.4	0.6	0.6
Sandwich thickness (d)		8.8mm	9.2mm	9.6mm
Sandwich Width (b)		50mm	50mm	50mm
Span length (L)		150mm	150mm	150mm
Ultimate force (F)		1328N	1484N	1396N
Face sheet Young's modulus (E)		61340MPa	61340MPa	61340MPa
Core shear modulus (G)		94MPa	94MPa	94MPa
Force		-1328N	-1328N	-1328N
FEA results	Deflection	3.07mm	2.63mm	2.35mm
Analytical results	Deflection	3.32mm	2.87mm	2.16mm

2.1 Finite element analysis (FEA)

Engineers invented the finite element method (FEM), which is a computational approach/technique for obtaining an approximate solution to engineering problems. FEA is efficient, time saving and less expensive. A measurement model that divides the structure into a number of minor subdivisions replaces the overall framework structure under evaluation (finite elements). If the mechanical problem is defined by a differential equation, the equation must be translated into a variational formulation (Galerkin method, mixed methods, discontinuous Galerkin method and many others), a discretization approach, one or more solution algorithms, and post-processing techniques define a finite element method. Moreover, finite element analysis (FEA) is used to check the correctness of theoretical predictions and compare them to experimental outcomes of structures. The computational method of finite element analysis (FEA) is used to predict how a product will react to forces, vibrations, heat, fluid movement, and other physical influences in the real world. Finite element analysis (FEA) is used to solve problems in a variety of fields, including heat transmission, vibrations, material strength, acoustics, and many more. In addition, to solve problems relating to domains in FEA, finite element methods (FEM) are applied and it include the galerkin method, weighted residual approach, and different numerical integration methods. It is entirely a mathematical method. Yang et al. (B. Yang et al., 2021) used FEA to simulate intra-laminar and inter-laminar delamination of the CFRP face sheets, as well as adhesive and honeycomb core failure. Hussain et al. (Hussain et al., 2019) modeled the honeycomb sandwich structure using ANSYS, a commercially accessible finite element tool, and fatigue simulations were performed to evaluate specimen life under load-displacement response. Harland et al. (Harland et al., 2019) developed a computational 3D FEA model to examine the nonlinear mechanical behavior of the re-entrant core under load. To investigate the dynamic deformation evolution of two face sheets and an auxetic reentrant honeycomb core, Xiao et al. (Xiao et al., 2019) developed a finite element (FE) model. Kumar & Patel (Kumar & Patel, 2019) calculated the dynamic response of the sandwich panel using the ABAQUS finite element modeling program, determining the structural behavior of honeycomb sandwich panels when subjected to blast loading on various cores (octagonal and square structures). Adams et al. (Adams et al., 2022) conducted finite element simulation to study the reaction of an elastomeric pre-buckled honeycomb structure under impact loads in order to determine its suitability for use in helmet liners. In general, every engineering discipline uses Finite Element Analysis, including aerospace, automotive, biomedical, chemicals, electronics, energy, geotechnical, biomedical, chemicals, manufacturing, and polymers industries.

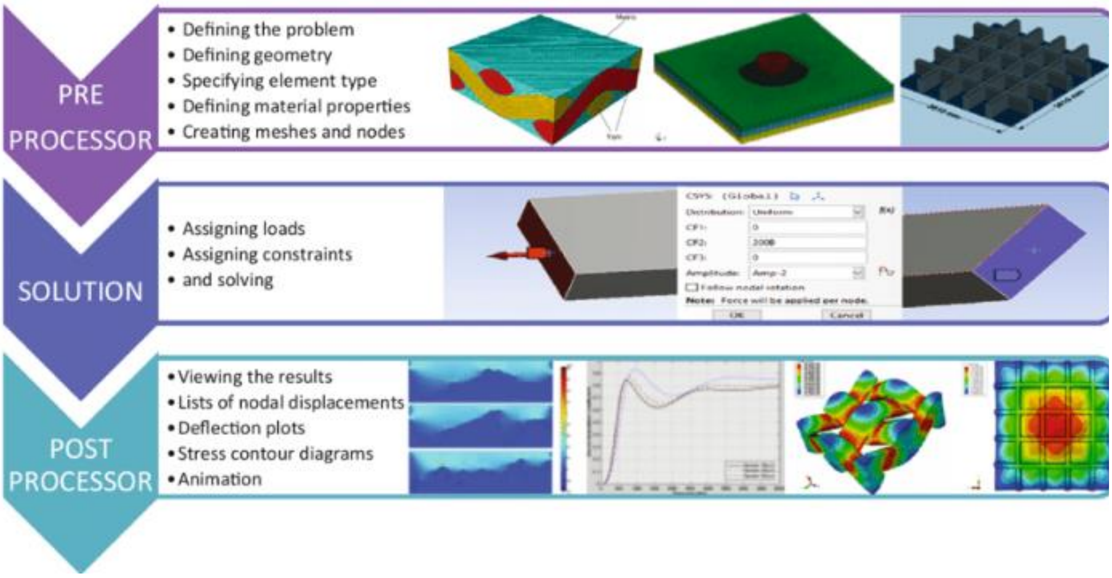


Figure 6. Overview of FEA adapted from (Naveen et al., 2019)

To estimate the deformation properties of the aluminium honeycomb material during the test, Khan et al. (Khan et al., 2019) performed a non-linear Finite Element Analysis (FEA) simulation using Altair® RadiossTM 13.0. Table 2 shows the research carried out on sandwich using finite element analysis.

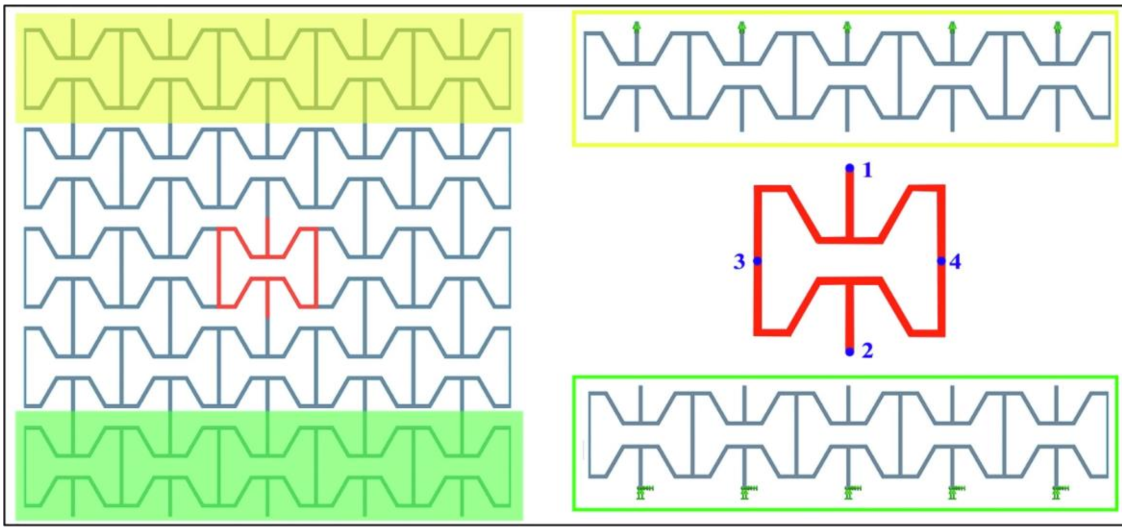
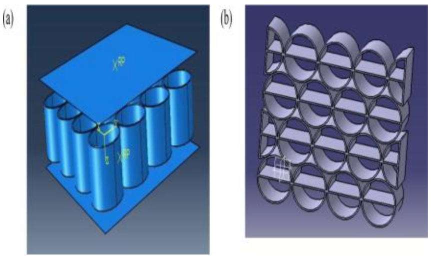
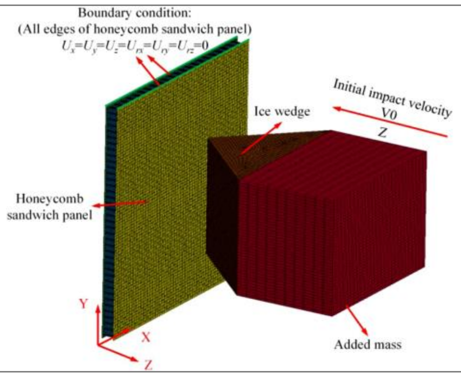
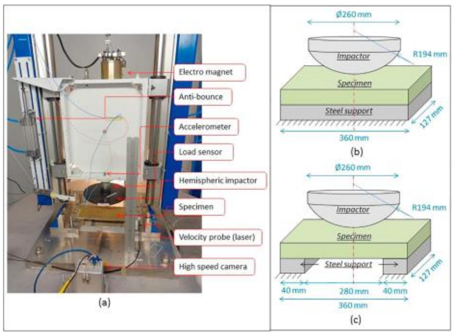
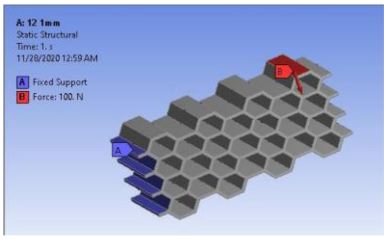
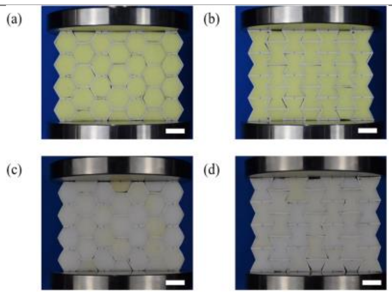
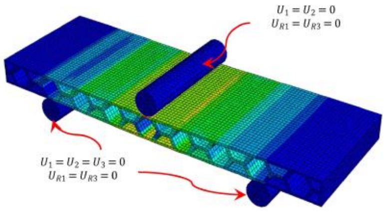


Figure 7. Boundary conditions being applied to the structure for FEA (Khan et al., 2019) .

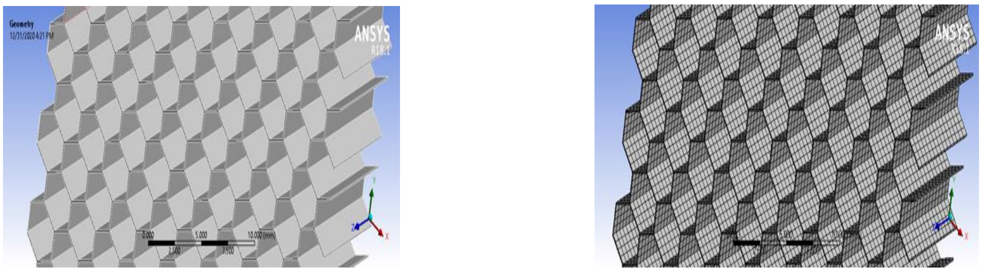
Table 2. Finite element analysis on sandwich

Ghongade et al. (Ghongade et al., 2019)	**Experiments and numerical**		**Abaqus-CAE.**	**Effect of reinforcement on the circular core honeycomb structure under axial com- pression behavior.**	**Honeycomb structures in dense packing mode and with reinforcements has higher load carrying capacity than that of the other conventional structures.**
Wu et al. (Wu et al., 2022)	Experiments and numerical		ANSYS/LS-DYNA	Dynamic responses and energy absorption characteristics of aluminum honeycomb sandwich panels (AHSPs) under ice wedge impact.	Nmerical results of ice wedge aluminum honeycomb sandwich panels (AHSPs) impact dynamic responses are consistent with the experimental results.
Audibert et al. (Audibert et al., 2019)	Numerical and experimental		ABAQUS	Considering the sandwich compression/shear coupling to take into account the transverse shear.	Under a low velocity impact, several dissipation mechanisms were implemented, which are characteristics of a sandwich structure (Skin damages, adhesive damages, and Nomex honeycomb damages).
Ahalya Kumar et al. (Ahalya Kumar et al., 2022)	Numerical -		ANSYS	Energy absorption and stability properties of gradient honeycomb structures (varying cell size across the width) compared to conventional or compliant structures (uniform cell size throughout the structure).	Gradient structures are more stable than compliant structures, and increasing cell parameters causes an increase in relative density, making the structure stiffer at the bottom.
Luo et al. (Luo et al., 2022)	Experiments and numerical		ABAQUS	Improving the mechanical properties of re-entrant honeycombs filled with slow and fast recovery foam.	Increasing the cell wall thickness, equally energy absorption capacity and auxetic effect of the slow recovery foam-filled re-entrant honeycomb

Pirouzfar & Zeinedini (Pirouzfar & Zeinedini, 2021)	Experiments and numerical		ABAQUS	Stress analysis on a honeycomb structure created with a 3D printer that uses fused filament fabrication (FDM).	The maximum normalized energy absorption is found in a honeycomb core with a wall thickness of 1.5 mm.

2.2 FEA of Honeycomb

Numerical tools used for differentiating and discretization (meshing) of geometries as shown in Figure 8. In modelling and simulation, variety of method are used to predict range of properties, namely, mechanical properties, thermal analysis, structural analysis, buckling analysis and stiffness. Xie et al. (Xie et al., 2020) investigated mechanical properties of combined structures of stacked multilayer Nomex honeycombs, established the finite element model of Nomex honeycombs and compared with experimental data. In-plane and out-of-plane crushing properties of the honeycomb core. According Sorohan et al. (S. Sorohan et al., 2019) to , the out-of-plane orientation of the core was discovered to be the strongest, absorbing a large amount of energy during deformation. The meshing employed by researchers for analysis is depicted in Table 3.



(a) (b)

Figure 8. Meshing (a) actual model (b) finite element model (Krishna et al., 2022)

Table 3. Meshing of Honeycomb

Element type	Nodes	Elements	Ref.
Polygonal mesh	630	314	(Nguyen et al., 2021)
SOLID186	6750		(Kadum Njim et al., 2021)
185-node	11,220	5000	(Kar & Srinivas, 2020)

Since the development of FEA in the aerospace industry in the 1950s by Boeing and Bell Aerospace in the United States and Rolls Royce in the United Kingdom. The first papers was published by M.J. Turner, R.W, since then it became an essential engineering tool. A lot of FEA Software's have been developed. Table 4 depicted the major FEA software's used and their companies.

Table 4. FEA software's and developer

Software	Developer	Platform
Mathematica	Wolfram Research	Linux, Mac OS X, Windows, Raspbian, Online service.
LS-DYNA	LSTC-Livermore Software Technology Corporation	Linux, Windows
MATLAB	MathWorks	Linux, Mac OS X, Windows
CosmosWorks	Dassault systemes solidworks corp.	Windows
Autodesk Simulation	Autodesk	Windows
ANSYS	Ansys Inc.	Windows, Linux
ABAQUS	Abaqus Inc.	Linux, Windows
Open FOAM	The OpenFOAM Foundation	Linux, Mac OS, and Windows

COMSOL	COMSOL Inc.	Windows, Mac, Linux

ANSYS and ABAQUS is the most used based on the graphic user interface (GUI), Moreover, component can be shared between most of the software, which makes FEA interesting. In the automotive sector, ABAQUS has greater penetration, while ANSYS is favored in the energy sector. ABAQUS has no room for SI unit, hence it requires a lot of focus and attention while ANSYS is flexible and lucid. ANSYS provides fine-sweep meshing and automated meshing (hexa-dominant, swept hex, hex-core, tetrahedral, and surface meshing) as investigated by Meyghani et al. (Meyghani et al., 2017).

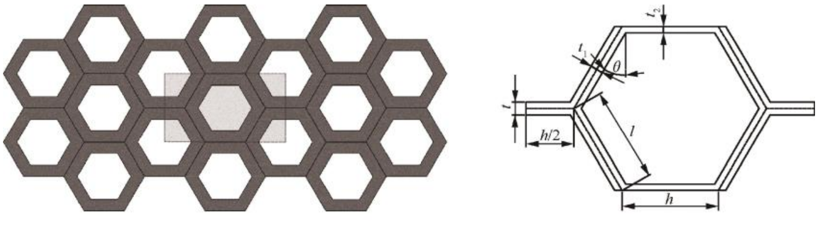
The load application, depends on the analysis form of honeycomb sandwich (static load, dynamic load, fatigue load, thermal load, and buckling load). The direction and velocity of loading defines on the kind of mechanical loading involved. Atiqah et al. (Atiqah et al., 2019) carried out hardness properties of honeycomb natural fiber reinforcement using Izod impact and Brinell hardness tester. Using commercial finite element software, the impact response of honeycomb sandwich structures was investigated., Dai et al. (Dai et al., 2020) investigated honeycomb sandwich structures using single and repeated impact testing.

2.2 Representative volume element (RVE) and Homogenization

RVE is a volume that statistically reflects a composite. That is volume that effectively includes a sampling of all microstructural heterogeneities (inclusions, fibers, voids, grains, etc.) that occur in the composite. Furthermore, hexagonal honeycomb consists of a ‘unit cell’ repeated many times in one or more spatial directions. This unit cell is usually a fraction of the size of the overall structure under investigation. Hence, in ANSYS Workbench a new feature called “Material Designer” has been introduced. An RVE is a material volume with a representative effective behavior of the entire material as defined by Aboudi et al. (Aboudi et al., 2013). Bargmann et al. (Bargmann et al., 2018) generated 3D RVEs for a broad class of materials. Babu et al. (Babu et al., 2018) used RVE to create microstructure of short fiber, which are efficient in predicting the stiffness of the short fiber composites.

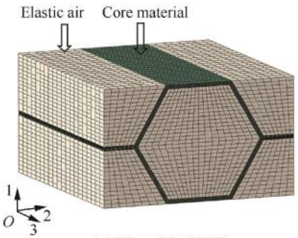
In honeycomb finite element modelling, the representative volume element was used to transform a honeycomb structure into a homogeneous and orthotropic substance through homogenization technique as proposed by Sorohan et al. (S. Sorohan et al., 2019). Safaei et al. (Safaei et al., 2018) carried out symmetric boundary conditions of platelet reinforced, allied unit cell model using ANSYS. Actually, different tools are used to evaluate honeycomb's RVE, such as Easy PBC in ABAQUS and material designer in ANSYS. These methods need material properties, fiber and volume division as inputs, RVE dimensions, the most convenient mesh size and form can be specified automatically and finally the RVE model can be solved. Qiu et al. (Qiu et al., 2017) predicted the effective elastic characteristics of honeycomb structures using a computational homogenization approach (CHT) based on the finite element method (FEM). Figure 9 depicts the representative volume element (RVE) of honeycomb core.

In order to compute the stresses in a system, the FEM is also used to explore a honeycomb core, due to the complex geometry an enormous number of elements are required, this vast number of elements makes calculation times exponentially increase as far as analyzing a major structure is concerned. However, simulating a million-unit cell lattice of volumetric elements or shell elements, it will be computational expensive. Hence, homogenization takes a unit cell and characterizes how it will behave in isolation, thereby indicating the stiffness matrix of the material. The number of elements can be significantly reduced by replacing the honeycomb core with a homogeneous core with orthotropic properties as shown Figure 10. The same rigidity as the wobbly center must be the homogeneous core. Wahl et al. (Wahl et al., 2012) carried out finite element simulation with a homogenized core calculating the shear stresses in the honeycomb core. Homogenization of the cellular structure to optimize the structure of the cellular structure (Ahmed et al., 2019).



(a) Representative volume element (RVE) in whole structure

(b) Size of RVE



(c) FE model of RVE

Figure 9. Representative volume element (RVE) (a) whole structure; (b) Size of RVE; (c) FE of RVE (Qiu et al., 2017)

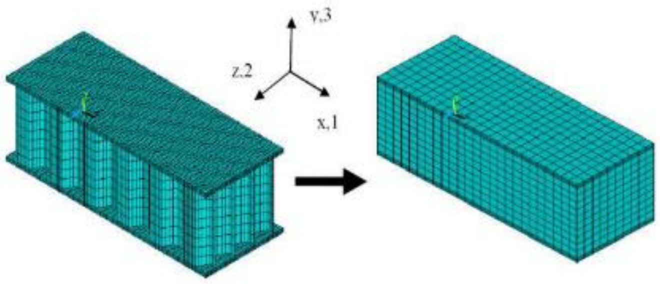


Figure 10. FE model of honeycomb and equivalent core (Ahmed et al., 2019)

3.1 Optimization and Design of experiment

Several optimization methods are applied to find the right parameters or the optimum value of a given property (strength, stiffness) in honeycomb sandwich structures. (Yogeswaran & Pitchipoo, 2020) performed an experimentation on the angle of the Abrasive water jet (AWJ) aluminum honeycomb, design philosophy of Taguchi was implemented. An analysis of thin-walled steel structure and aluminum honeycomb energy absorption potential was performed by Yang et al. (Yang et al., 2018) using analysis of variance to investigate the impact of dispersed honeycomb intensity on crashworthiness indicators at four levels. ANSYS has an inbuilt program for design of experiment and optimization which saves time significantly, for instance, parameter feature connects input and outputs to the parameter interface in the workbench project. Dutra et al. (Dutra et al., 2019) carried out design of experiment on five parameters with different levels, in order to determine the essential material to change orientation, add or remove, for effective flexural strength and optimization as shown in Table. 5. Moreover, design of experiment is a major step for researcher that guides directly to the desired design output. Figure 11 shows geometric factors of the honeycomb core.

Table 5 Parametric conditions for the FE model (Dutra et al., 2019)

Geometric factors	Levels			
Height of cell [mm]	5	10	20	30
Honeycomb geometry	Hexagon		Rectangular	
Cells per honeycomb	42	84	126	
Web thickness [mm]	1	2	3	
Facing thickness [mm]	1		2	

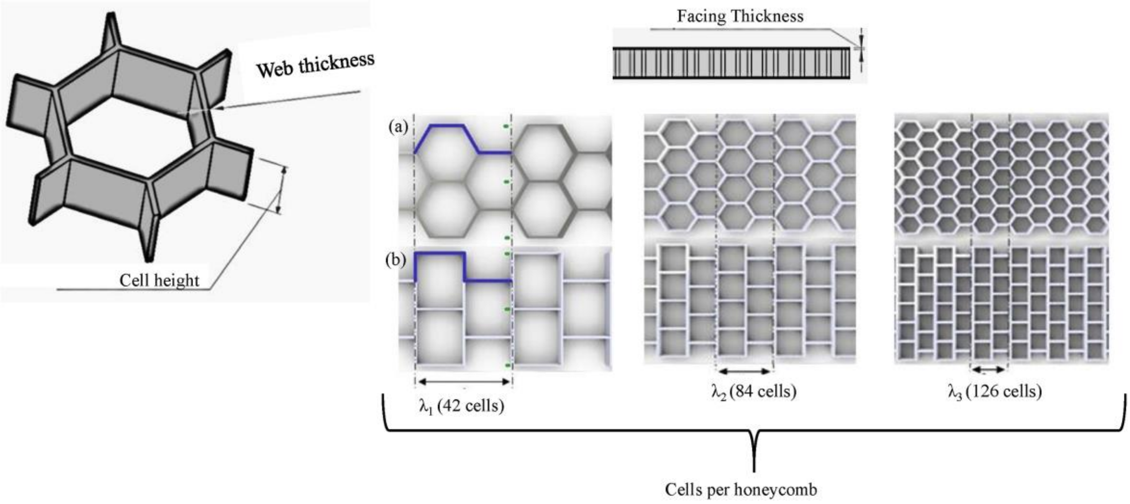


Figure 11 Geometric factors of the honeycomb core composite sandwich (Dutra et al., 2019)

4. Discussion

Finite element analysis investigated in different commercial software's, but ANSYS and ABAQUS is mostly considered. Honeycomb sandwich structure can fail in different ways, various theories were used by researchers to study it failure mechanism. Honeycomb sandwich is often treated as a beam element, many researchers used different theories of beam. Safaei & Fattahi (Safaei & Fattahi, 2015) carried out different kinds of beam theories included Euler-Bernoulli theory of beams, Timoshenko beam theory and Reddy beam theory to analyze composite beam buckling behavior. Skin failure (facial yielding, intra-cell dimpling, and face wrinkling) and core failure are two common modes of failure (core shear and local indentation) (Petras, 1999). However most of the analysis used three point bending test and tensile test set-up, moreover, majority of the researcher's added boundary conditions on the honeycomb sandwich, treated the sandwich as simply supported beam (Birman & Kardomateas, 2018; Gao et al., 2020; Roy, Kweon, et al., 2014; Roy, Park, et al., 2014). A lot mimic the 3-point bending testing, adding two supports and a pusher. Gibson and Ashby derive nine engineering constants for a honeycomb core with constant wall thickness, and include shear and axial deformation effects. Table 6 shows some of the application of FEA in honeycomb structures. However, the governing differential equations for the flexural vibration of honeycomb structure inline of displacement is always presented three plates theories (CPT IPT, TSDPT)

Table 6: FEA applications on sandwich

Honeycomb core/ sandwich structures	Materials	Numerical analysis	Analytical	Platform	Objective	Remarks/key FIndings	Ref.
Inconel 718	Perforated skin sandwich structures (SSPS) perforated core sandwich structures (SSPC)	FEA	Homogenization heat treatment	ANSYS/ SolidWorks	Heat treatment	Heat-treated sandwich structures (SSPS) have a compressive strength 65% higher than (SSPC).	(Zaharia et al., 2020)
Aluminum sandwich panel	Aluminum	FEA		ANSYS	Velocity impacts.	The depth of the core damage was found to be entirely dependant on the height of the adhesive fillet that connects the face sheet to the core. The configuration of the cellular core had no effect on the depth of core damage.	(Zaharia et al., 2020)

Sandwich panel with laminate faces	Unidirectional fiber reinforced composite.	FEM	Shear Deformation Theory	ANSYS	Vibration response	Natural frequencies of sandwich and vibration response was clearly observed.	(Kormanikova et al., 2021)
Sandwich roof panel with multilayer polyurethane foam core	Wave shaped GFRP webs infilled with multilayer PU foam. Trapezoidal shaped GFRP webs infilled with multilayer PU foam. Rhombus shaped GFRP webs infilled with multilayer PU foam.	FEM		ANSYS	Flexural performance of Glass Fibre	GFRP sandwich panels with Type 3 core is best for roofing. Total deformation decreased as the (GFRP) piled increased.	(Manjusha & Althaf, 2020)
Soneycomb sandwich	Mechanics of structure genome (MSG). Structure Gene (SG).	FEM	Gibson and Ashby correlations	ABAQUS	Bending stiffness	MSG approach is more efficient than direct numerical simulation (DNS).	(Zhao et al., 2019)
Aluminum and sandwich panel	Lightweight T-joint		Adhesion interfaces	ANSYS	Load bearing/tension load	Geometry joint strength enhanced.	(Omidali & Khedmati, 2018)
Honeycomb sandwich panels (square and octagonal core structure)	1-3kg Trinitrotoluene (TNT)	FEA	Friedlander equation	ABAQUS	Dynamic response	Experiment results have been used to validate the square honeycomb sandwich panel's top and back face deflections.	(Kumar & Patel, 2020)
Nomex honeycombs		FEA	Gibson and Ashby correlations		Mechanical properties	Stacked honeycombs produce controllable, orderly, graded response and energy level.	(Xie et al., 2020)
Honeycomb cores	vinylester matrix reinforced with jute fabrics	FEM		ABAQUS	Elastic response/flatwise compression.	In contrast to commercially available cores, the jute-vinylester cores have high compression strengths. jute-reinforced cores is goof for compressive static load.	(Stocchi et al., 2014)
Sandwich plates (Miura-ori folded core)		FEA	Plastic hinge	ABAQUS/Explicit	Plastic bending moment and elastic buckling moment	As the side lengths increase, softening due to core buckling is more likely to occur. As the side lengths increase, energy absorption capacity decreases.	(Xiang et al., 2018)
Honeycomb sandwich (polypropylene core)	Thermoplastic	FEA/experiment			Energy absorption	Influence of skin panel and Influence of honeycomb core was explained graphically.	(Gao et al., 2020)
Honeycomb sandwich structures		FEM		ABAQUS/Explicit	Impact response	The impact decreased exponentially with increasing impact energy.	(Dai et al., 2020)
Hexagonal/Rectangular Honeycomb	Piassava laminate composite	FEA/experiment	Classical Beam Theory	ABAQUS	Failure/elastic flexural properties	Rectangular honeycomb core has the most flexural strength. Core geometry significantly affects stiffness panel and strength.	(Dutra et al., 2019)

In the last two centuries, classical theories have been designed to model global membrane-bending mechanics. Therefore, present finite element equations are very similar to finite elements based on classical plate theory, but differ in the selection of transverse displacement function. Rajaneesh et al. (Rajaneesh et al., 2020) used new first-order shear deformation theory (NFSDT) to derive total potential energy, stiffness, mass, and force matrices. Altenbach & Öchsner

(Altenbach & Öchsner, 2020) investigated dimensional reduction of plates turning the 3D problem into a 2D plate model. The indentation failure of sandwich plates is describe by (Petras, 1999). In case of kinematic assumptions for the transverse shear stress and strain component most researchers used First-order shear deformation theory. (Higher order theories) provide exact figures as investigated by Grover et al. (Grover et al., 2014), although they are computationally expensive. The major advantage of-HSDT is the exclusion of high-order derivatives and the effortless compliance of boundary conditions.

Different boundary conditions were assigned, such like clamped, simply supported, and free boundary conditions, as well as ANSYS RVE periodic boundary's conditions in material designer.

Honeycomb strength is evaluated in three distinct axes W-transverse direction (weight), L-ribbon direction (length) and the T-direction which is the cell depth. Honeycomb strength are categorized into in-plane properties and out-of-plane properties. The out-of-plane compressive properties of woven and UD laminated carbon fiber composite curved honeycombs were investigated by Chen et al. (X. Chen et al., 2021), results demonstrate that when only the curvature radius is reduced or the wall thickness is increased,, the out-of-plane compressive strengths increase. Energy absorption is higher if the honeycomb is compressed along the cell depth.

5 Conclusion

A detailed analysis and objective comparison of recent studies on application of finite element analysis to honeycomb sandwich structure is discussed in this report. Many researches focused on mechanical properties of honeycomb sandwich structure such as Buckling, crushing, in-plane properties and out-of-plane properties, tensile, impact, flexural effect, taking into account both numerical and theoretical studies, while few researches investigated thermal properties, vibration. In the future, some energy should go into loading effects of honeycomb sandwich structure at very high temperature and heat transfer capacity of different sandwich. A lot of researches details of experiment is by no means lucid, factors like web thickness, ply angle, weight of sandwich, resin used, area/volume of the honeycomb structure and number of cells in the sandwich are not well detailed while some was omitted. The most effective honeycomb load-bearing components is the carbon fiber composite curved honeycombs (CCCHs). Honeycomb sandwich structures will play a vital role, such as anti-collision, and load bearing, so on. For explicit analysis, ANSYS relies on a cooperation with DYNA, but ABAQUS has it all integrated. Moreover, many researches used ABAQUS for explicit analysis and automotive designs, while in energy related designs ANSYS were used. In general, ANSYS has a good GUI (graphical user interface), while ABAQUS has a better API (application program interface). In the future there would be wide implementation opportunities for honeycomb structures in weight-sensitive environments, such as advanced aircraft, deep sea and deep space exploration.

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