Advances in Materials Research, *Vol. 14, No. 4 (2025) 309-326*
https://doi.org/10.12989/amr.2025.14.4.309

Interpretation study of quasi-static uni-axial compression analysis of cellular panels with machine learning application

Shrivathsa T.V.*[1,2], N.P. Puneet[2a] and Vijayasimha Reddy B.G.[3b]

[1]Department of Artificial Intelligence and Machine Learning, Shri Madhwa Vadiraja Institute of Technology and Management, Bantakal, Karnataka, India, 574115
[2]Department of Automobile Engineering, Dayananda Sagar College of Engineering, Bengaluru, Karnataka, India, 560111
[3]Deparment of Mechanical Engineering, Vemana Institute of Technology, Bengaluru, Karnataka, India, 560034

(*Received June 6, 2024, Revised July 1, 2025, Accepted July 30, 2025*)

Abstract. The study aimed to evaluate the energy absorption behavior of cellular sandwich panels made of banyan wood skins and an aluminum honeycomb core under quasi-static loading conditions. The study analyzed two different setups: Type-I panels, which had banyan wood skin plates whose fibers are aligned in plane to the loading axis, and Type-II panels, which had skin plates whose fibers are aligned perpendicular to the loading axis. Both variants reliably aligned the aluminum honeycomb core with its cell axis parallel to the loading direction. An analysis was conducted on the behavior under quasi-static loading circumstances, and the capacities for absorbing energy were measured. The results showed that the energy absorption capabilities were improved during fibers along the cut (Type-I) situations in quasi-static circumstances. Type-I sandwich panels demonstrated exceptional effectiveness in absorbing impact energy, making them especially suitable for applications. Further interpretation of same is developed based on the application of machine learning algorithm. This algorithm considers the wood and aluminum properties and dimension to generate load v/s displacement behavior. The machine learning algorithm also shows the correlation of predicted data found is 99.92% with respect to actual. The algorithm best suits to find the behavioral pattern without conducting experimentation of specified sandwich panels in future application.

Keywords: aluminum; linear regression; machine learning; sandwich panels; wood specimen

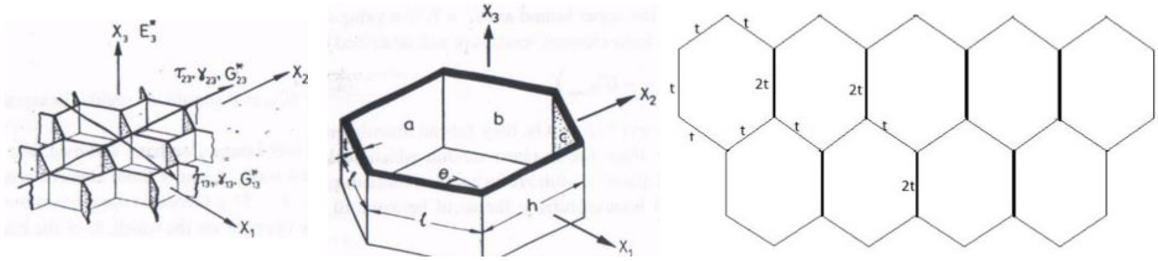
1. Introduction

Honeycombs are frequently employed as cores in sandwich panels. It is important to understand that the honeycomb core's main purpose is to bear both normal and shear loads within planes that align with the axis of the hexagonal prisms, specifically the X3 direction shown in Fig. 1. When oriented in this manner, the cell walls undergo extension or compression instead of bending. Let's consider a honeycomb with a low density, where the thickness of all the walls is the same, denoted as 't' and t << l. This assumption may be extended to honeycombs with walls of different thicknesses

---

*Ph.D., Assistant Professor, E-mail: shrivathsa-au@dayanandasagar.edu, shrishatv@gmail.com
[a]Ph.D., Assistant Professor, E-mail: puneet-au@dayanandasagar.edu
[b]Professor, E-mail: bgvsreddy1@gmail.com

http://www.techno-press.org/?journal=amr&subpage=5 ISSN: 2234-0912 (Print), 2234-179X (Online)



(a) (b) (c)

Fig. 1 (a) A honeycomb carrying loads on the faces normal to X_3, (b) One cell, showing the walls a, b and c (Paravano 2017) (c) Thickness of honeycomb structure

without much difficulty (Zhu and Sun 2021). By doing so, it is possible to generate a wide variety of crush strengths, ranging from 0.175MPa to 55MPa.

Honeycomb panels are extensively utilized in various industries, including packaging, aviation, furniture, and building, due to its lightweight, strong structure, and beneficial cushioning properties. Honeycomb panels are commonly employed as cushioning material in logistics operations to endure vibration and shock, effectively absorbing energy and safeguarding products against harm.

The honeycomb may be easily molded and designed to create energy absorbers that can adapt to a wide range of demands, including both constant and variable forces of high and low gravitation (Vijayasimha Reddy *et al*. 2014). Honeycombs undergo deformation through many causes. When subjected to in-plane loading, the cell walls initially undergo bending, resulting in linear elasticity that may endure strains of up to 10%. This phenomenon is achievable due to the honeycomb's resemblance to a spring. The specific arrangement of its components permits significant deformation of the structure while causing minimal strain on its individual parts. When subjected to out-of-plane loading, the cell walls undergo extension, compression, or shear, resulting in a significantly increased stiffness of the structure.

If the cell walls consist of a deformable substance, the honeycomb undergoes gradual deformation; however, if it is composed of a fragile substance, it experiences crushing and fracturing in a brittle fashion. The in-plane strength is consistently lower than the strength for out-of-plane loading due to the prevalence of bending in the former case and axial deformation in the latter. An analysis can be conducted on each mechanism, resulting in expressions for the strength of each type of honeycomb. The identification and analysis of mechanisms are validated through comparisons with experiments, providing confidence in their accuracy (Ciepielewski *et al*. 2022). Honeycombs exhibit atypical behavior when subjected to biaxial loads. The dominance of cell wall bending in the in-plane characteristics of hexagonal cells under uniaxial stress can be fully eliminated by applying adequate biaxial loads (Papka and Kyriakides 1999). Subsequently, the cell walls experience axial yielding, creep, or fracture, resulting in a significant increase in strength. The honeycombs exhibit yield and brittle failure surfaces that are highly elongated ellipses. It is important to consider this unique shape when constructing structures incorporating honeycombs.

Avoiding unwanted collisions plays as active safety. Preventing the loss and minimizing the damage resulting from unavoidable collisions is passive safety. Active safety can be achieved through good designs. Passive safety focuses on the design of structures that are able to withstand crashes and incorporate extra safety features to avert disasters in the event of unintended collisions.

Sandwich panels are notable for their ability to exhibit the same strength as a solid material, while having a much lower weight (Yadav and Chhapkhane 2012). The demand for materials that are both

Fig. 2 Sandwich panel of wood and aluminum honeycomb

stronger and lighter is growing in the transportation and aerospace sectors, and sandwich panels are meeting this requirement. The typical composite sandwich structure consists of two primary components: the outside skin and the inner core. The sandwich panel skins consist of diverse materials and serve as the exterior layers. Wood, aluminum, and plastics are frequently utilized. In recent times, there has been a shift towards utilizing sophisticated composite fibers and resins for the production of skin material.

The core materials contribute significantly to the desirable qualities of the panels. Each core possesses distinct benefits. For instance, balsa wood serves as a lightweight core with exceptional strength, but it is susceptible to rotting or molding when exposed to moisture. While foam is often less rigid than balsa, it is resistant to moisture and possesses insulating characteristics (Fathi *et al.* 2013). Honeycomb material has high strength and rigidity, however, it is frequently more costly and presents challenges in achieving a high-quality link between the outer layers and the core. In general, the core provides support to the sandwich, while the skins serve as a protective layer for the core. Sandwich panels replicate the characteristics of a solid structure while weighing only a fraction of the original weight.

Honeycomb structures developed by humans include sandwich composites containing honeycomb cores. Fig. 2 displays an illustration of a honeycomb structure. Honeycomb structures are artificially created by utilizing a range of materials, which are selected based on the desired purpose and necessary attributes. These materials can include paper or thermoplastics, which are suitable for applications with low strength and stiffness and low loads, as well as aluminum or fiber reinforced plastics, which offer high strength and stiffness for high-performance applications. (Usta *et al.* 2021, Vijayasimha Reddy *et al.* 2014).

The mechanical response of a sandwich panel is contingent upon the characteristics of the face and core materials as well as its geometric configuration. The panel in most applications must possess a minimum needed level of stiffness, ensuring it does not fail under the maximum service stress while still striving to be as lightweight as feasible.(Wang *et al.* 2021). Elements primarily designed for energy absorption can also function as secondary structural components of lesser importance.

Applications of Energy absorptions (EA) include the bottom of lift shafts or nuclear fuel funnels, roadside crash barriers (Usta *et al*. 2021, Vijayasimha Reddy *et al*. 2014). The swift progress of technology in recent years has necessitated a fresh focus on safety in transportation and industrial sectors. The choice of a suitable energy absorber is highly dependent on its specific application and the intended reaction at impact or uniformity. Nevertheless, in order for an EA to be efficient, it must possess the subsequent attributes:

1. A high specific energy absorbing capacity, which refers to the amount of energy absorbed per unit mass, is crucial for energy absorbers (EAs) used in transportable constructions such as automobiles and aircraft.
2. In situations when a compact-sized energy absorber is needed, a high energy-dissipation density, which refers to the amount of energy absorbed per unit volume, is essential.

The aluminum honeycomb core is a very effective energy absorber that offers significant advantages compared to other materials used for energy absorption. The material possesses a high ratio of crush strength to weight, exhibits a linear force curve with a consistent load, and has the ability to absorb energy over a significant stroke length. Cells undergo structural deformation and folding, resulting in a consistent load that may be adjusted by employing different alloys, thicknesses of foil, sizes of cells, and arrangements of cells (Wang *et al*. 2021). Aluminum honeycomb is an exceptionally reliable, efficient, and practical energy-absorbent material due to its minimal rebound and lightweight nature. Honeycomb energy absorbers have extensive applications in the automobile sector for the purpose of impact mitigation and as crash test barriers. Honeycomb's energy-absorbing properties are utilized in ensuring the safety of nuclear reactors and aerospace sectors (Zhu and Sun 2021).

1.1 Linear-elastic deformation of honeycomb and woods

The California Institute of Technology conducted pioneering studies on the plastic crushing of honeycombs under axial loads, which were initially published by McFarland in 1963 and 1964. Comprehensive information was given regarding the deformation and crushing behavior of honeycombs composed of regular hexagonal cells and densely packed cylindrical tubular parts.

A shear failure mode is characterized by a significant and continuous collapse of the structure. Wu and Jiang conducted a research investigation where they subjected aluminum honeycombs to axial compression and then compared the obtained results with earlier theoretical predictions. They discussed the effects of cell size, material strength, the number of cells and cell wall thickness on the mean crushing stress. Their experimental observations (crushing strength and plastic fold length) were found to significantly overestimate the predictions of the theoretical model, which were also used by the manufacturer (Wu and Jiang 1997).

A cellular solid consists of a network of solid struts or plates that are interconnected to generate the edges and faces of cells. Wood is a complex and intricate construction material. Under high magnification, it exhibits the characteristic structure of a fiber-reinforced composite. When viewed at a lower magnification, the material appears to be composed of cells that have a high degree of anisotropy. The fiber-reinforced cell walls of wood have a similar composition in lay-up, with the fundamental distinction between different types of wood being their variations in cellular structure. Primarily, it is the comparative thickness of the cell walls, and consequently, the comparative density, that governs the mechanical characteristics of wood. Age, moisture content, strain rate and temperature all have an effect (Gerhards 1982).

In woods of higher density, the long, axial cell walls yield and then undergo local plastic buckling.

The first mechanism is analyzed by equating the work done in moving the applied load through a displacement, δ, to the plastic work done in the corresponding deformation of the faces of the end cap (Usta *et al.* 2021). Several cellular solids, such as wood, cancellous bone, and coral, are capable of withstanding significant static and cyclic loads over extended periods. The utilization of natural cellular materials in structural applications by humans dates back to ancient times. Wood remains the most extensively utilized material for construction worldwide. Enhanced comprehension of how wood's characteristics are influenced by density and loading direction can result in improved design using this material. Furthermore, artificial foams and honeycombs are being utilized more frequently in applications where they serve a genuine structural purpose (H L Schreyer and Q H Zuo 1995, Zhang and Ashby 1994).

Modern airplanes utilize sandwich panels composed of glass or carbon-fiber composite skins, which are divided by aluminum or paper-resin honeycombs, or rigid polymer foams. This construction results in a panel that possesses exceptional specific bending stiffness and strength. The identical technology has extended to other applications where the mass is of utmost importance (Lima *et al.* 2011, Usta *et al.* 2021).

1.2 Machine learning applications

Intelligent systems rely on features that are obtained by extracting information through the process of data mining. An analysis of the data relationship and concealed data patterns has yielded significant experiment insights and has demonstrated its value in many data mining applications. When developing an intelligent system, it is necessary for a person to choose the most effective and adaptable technique in order to create a strong and resilient system. Therefore, after careful evaluation of various approaches and their outcomes, it is imperative to prioritize the development of the most accurate predictive model. The classifier and regressor (Upadhya *et al.* 2024, Jiang *et al.* 2024) (class of machine learning (ML) model) is a crucial component in the majority of intelligence systems. Several classifiers and regression model utilize the pattern matching technique to ascertain the optimal match. The adaptation of classifiers relies on the specific pattern or behavior of observed data (de Naurois *et al.* 2019).

The field of materials design has witnessed a surge in popularity of ML technologies in recent years, capturing the attention of numerous individuals. The algorithms are capable of doing linear and nonlinear regression analysis on input and output data. They may establish intricate correlations and rules, and make predictions about material qualities by learning from the available data (Wang *et al.* 2021). The utilization of various machine learning methods has led to the increasing popularity of material property and behavior prediction (Luger 2005, Rai and Mitra 2021, Jiang *et al.* 2024, Jiang *et al.* 2024). Summarization of key contributions of literature are listed as follows.

- Few researchers have developed a machine learning linear regression model to forecast the deformation behavior of aluminum-honeycomb and banyan wood composite sandwich panels.
- Past studies have achieved a 99.92% correlation between experimental and machine learning-predicted load-displacement data.
- Type I (grain-aligned) panels exhibited superior energy absorption capability compared to Type II (cross-grain) designs.
- Few studies have proposed a reusable machine learning approach for forecasting energy absorption behavior without necessitating repetitive physical testing.

Study of machine learning with respect to prediction behavior of energy absorption in sandwich panels made from wood and aluminum is to improve the performance application. It is possible to

Table 1 Material properties

Material	Density (kg/m^3)	Specifications
Banyan (wood)	615.81	l*b*h = 100*100*15 mm. (Type -I and Type-II)
Aluminum Honeycomb	77	Shape of the cell - Hexagonal Material - 3003 Aluminium foils Aluminum Foil thickness = 0.068 mm l*b*h = 100*100*30 mm. cell size = 6.3 mm

* l = length, b= width, h = thickness of wood specimen

identify the behavior using relationships like material's make-up, the panel's shape, and its mechanical qualities by using the load v/s displacement behavior. Machine learning (ML) models can be built to forecast how these systems would react in different scenarios by examining their behavior in connection to variables such as material composition, panel geometry, and mechanical qualities. This prediction ability is especially useful for choosing economical materials for certain applications and optimizing energy absorbers. However, there is still a discernible lack of research that combines ML models with practical investigations, particularly for complicated structures like sandwich panels, even with the increasing usage of ML in engineering. Such multidisciplinary research is scarce, which makes it difficult to create comprehensive design frameworks that could improve material performance in real-world situations by utilizing both empirical data and predictive modeling. This research study aims predict the material behavior based on machine learning technique. This approach may help to get useful information from sandwich panels without doing experiment in future applications.

2. Experimental investigation

2.1 Test materials and specimens

In this study the cellular solids viz. wood and hexagonal aluminum honeycomb have been chosen to prepare cellular sandwich panels to test under quasi-static uni-axial compression loading conditions. Banyan wood specimens were cut from well-seasoned woods and prepared as per ASTM 7007 standards, of size 100*100*15 mm for both along and across the grain configuration. The hexagonal honeycombs made of aluminum 3003 alloys manufactured by Aluminum Honeycomb India Limited as per ASTM C-365 standards were bought and sized to 100*100*30 mm. The detailed specifications and properties are listed in the Table 1.

Weight of the panels was measured and the volume and density were calculated. Type I panels were prepared with wooden skin kept along the grain configuration whereas Type II panels were prepared with wooden skin kept across the grain configuration. These Type I and Type II panels were kept on both sides of honeycomb during respective experiments.

Uni-axial quasi static compression tests were conducted on cellular sandwich panels of Type I and Type II in a 400kN Electronic Version Universal Testing Machine. These panels were tested in uni-axial compression loading at a deformation rate of 10mm/min. The crushing behavior of these panels were observed and recorded. The load deformation curves were plotted for each panel.

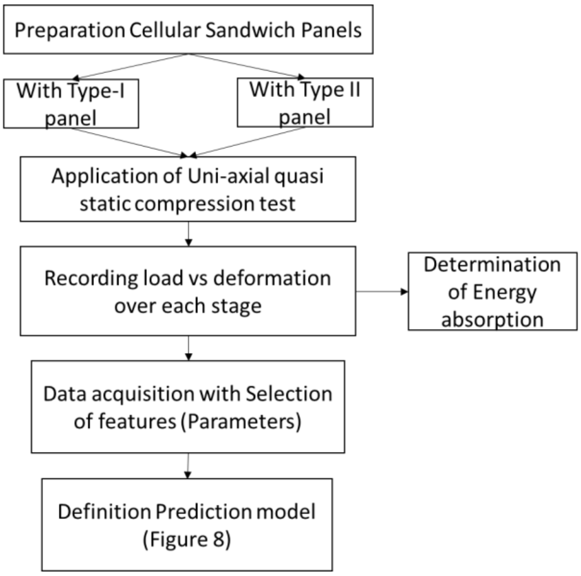


Fig. 3 Methodology Overview

Fig. 4 Electronic Universal Testing machine (UTES-40)

Cellular panels (Type-I) of wood skin and aluminum honeycomb core were made in which the aluminum core is placed in out -of plane direction, the bottom and top wooden plates were placed along the grain configurations (load acting along the grains of wooden panel). Cellular panels (Type-II) of wood skin and aluminum honeycomb core were made in which the aluminum core is Uni-axial quasi static compression tests placed in out -of plane direction, the bottom and top wooden plates were placed across the grain configurations (load acting across the grains of wooden panel). The energy absorbing capacities for cellular panels of Type I and Type II were calculated and results were tabulated. A comparison of energy absorption and specific energy absorption was made between the cellular panels of Type I and Type II. The overview of sequential procedure of the methodology is as shown in Fig. 3, which encompasses: 1. Preparation of sandwich panels 2. Data acquisition from trials, 3. Selection of features (material density, grain orientation, thickness), 4. Model training and testing with Python, 5. Prediction of deformation behavior. Process in continuation to Fig. 3 is represented in Fig. 8.

2.2 Experimental procedure

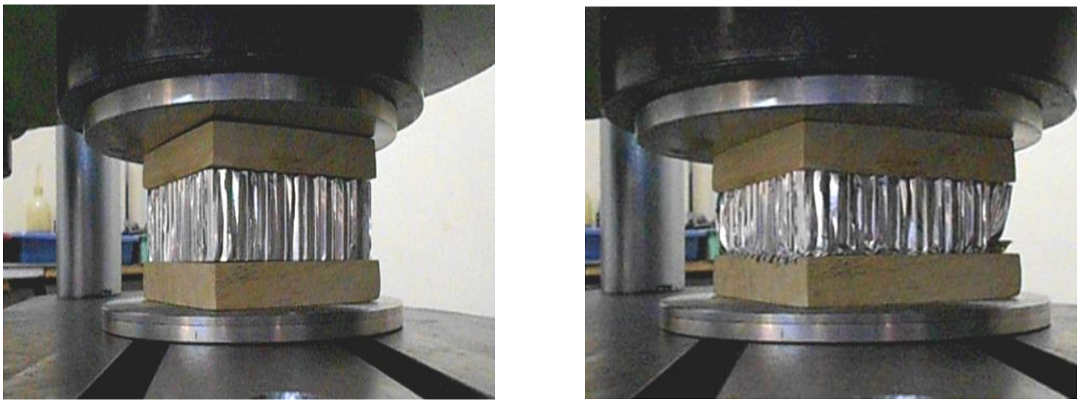
The compression experiments (quasi-static) were conducted using the Electronic Universal Testing Machine type UTES-40 (Fig. 4) in a quasi-static manner. The apparatus comprises of two parallel stiff steel plates. The upper crosshead is immobile, whilst the movement of the lower crosshead is regulated by a computer-controlled hydraulic mechanism, which can be manually overridden. Prior to commencing each test, the system is provided with the necessary experimental settings, including the crosshead speed, maximum load or displacement, and data sampling rate. The computer stores all gathered experimental data, facilitating convenient future retrieval. The machine measured two primary variables during the experiments: the load exerted by the lower cross-head and the movement of the cross-head. With these numbers, several other significant statistics like as stress, strain, Young's modulus, and more can be determined, as long as the required extra information is provided. By connecting a printer to the computer, it becomes possible to produce printed copies of graphical plots depicting the experimental results. The UTM has a maximum load capacity of 400kN, as shown in Fig. 4. The gauge length refers to the specific length that is being examined or observed during the experiment on the specimen. The gauge length of a specimen maintains a consistent standardized ratio to the cross-sectional dimension for certain purposes. Upon activation, the machine initiates the application of a progressively higher load on the specimen. During the tests, the control system and its accompanying software document the amount of force applied and the resulting elongation or compression of the specimen.

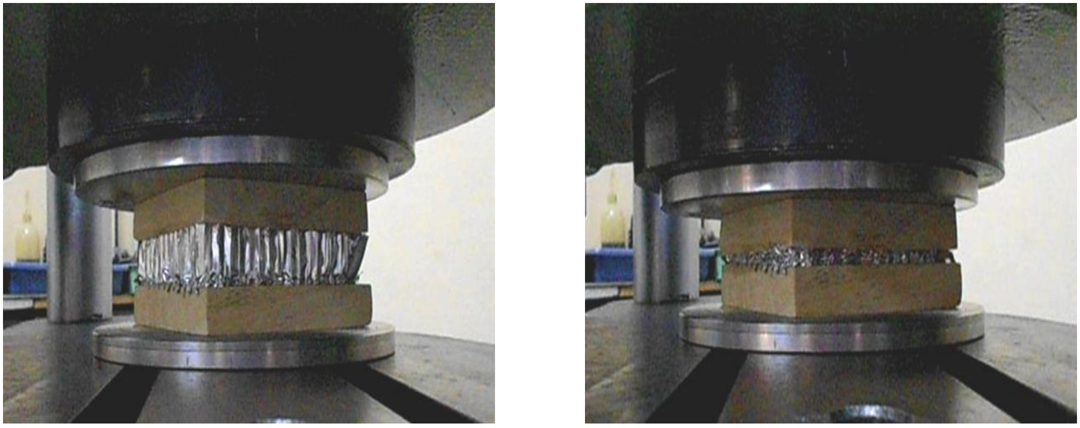
3. Deformation mechanism of cellular sandwich panel

Fig. 5 shows a uni-axial compression test on wooden face plates with grains aligned along the direction of the loading axis. The Fig. 6 shows the same test, but with grains oriented across the loading axis, using an aluminum honeycomb core sandwich panel. The load-displacement curve exhibits elastic, completely plastic, and locking features, as depicted in Fig. 7. The initial collapse happened when the load reached a magnitude approximately double that of the normal stable load, resulting in a gradual crushing process. The compression of layers of cell walls occurs uniformly throughout the full volume of the honeycomb core under a constant plateau tension. This leads to the creation of creases that resemble those seen in the axial collapse of tubular constructions under quasi-static loading conditions. (Dong *et al.* 2021).

In the subsequent phase of compression, the compression of the individual layers of cells reaches its limit and additional deformation occurs due to the compaction of the solid phase of the wooden plate. The solid object starts to penetrate the top and bottom wooden face plates, causing the wood to extend into the holes. This can be seen by the localized change in shape of the wood's cellular structure at the points where it meets the solid object. Subsequently, the cell wall structure of the wood undergoes significant elastic deformation, leading to an increase in load. This is due to the fact that wood offers greater resistance when compressed in the direction of its grains.

At a later stage, the cellular structure of the wood undergoes bending, buckling, and plastic collapse. This is shown by the formation of bands, which often start at the ends of the wood specimen


Stage I Stage II


Stage III Stage IV

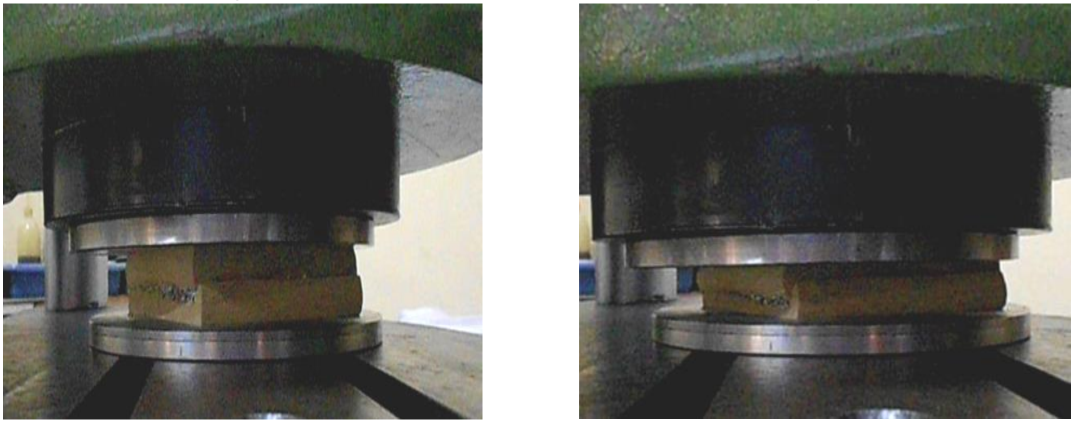
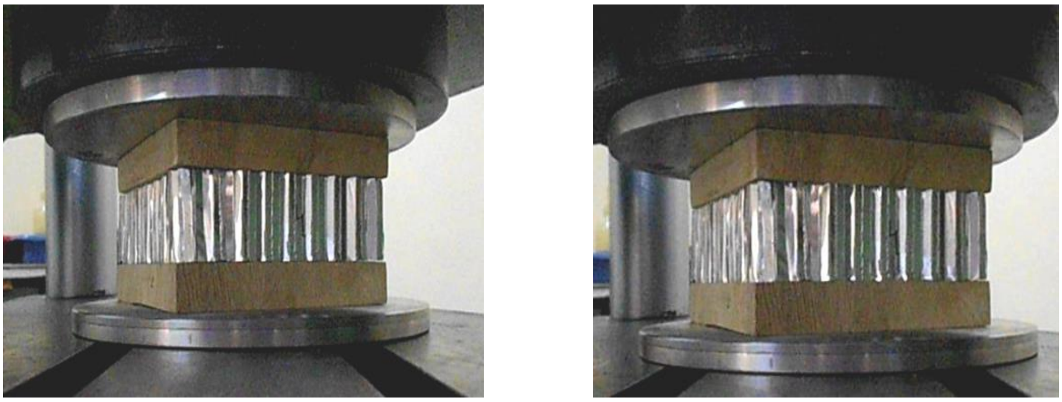

Stage V Stage VI

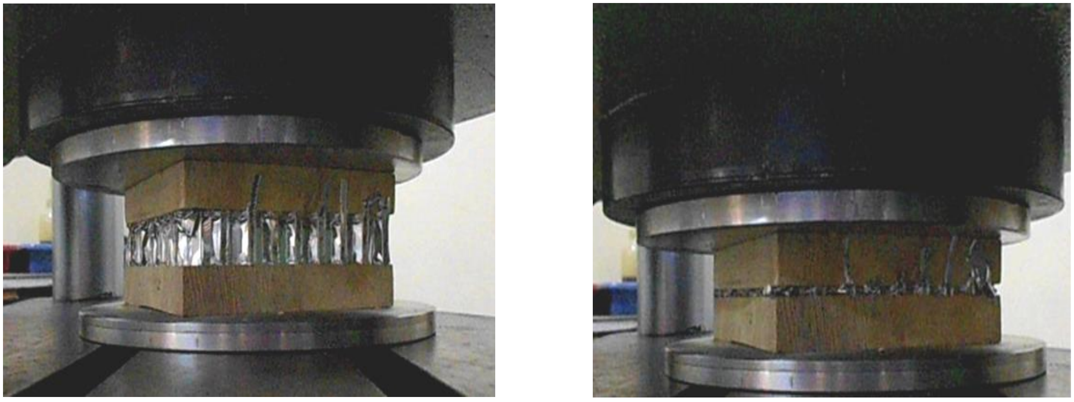
Fig. 5 Quasi-Static compression of banyan-Aluminium honeycomb cellular sandwich panel (Type I) along the grain configuration (Stage I – Stage VI)

next to the loading platens (Da Silva and Kyriakides 2007). Therefore, the solid perforated plate effectively enters both wooden face plates through shear deformation, similar to a blanking



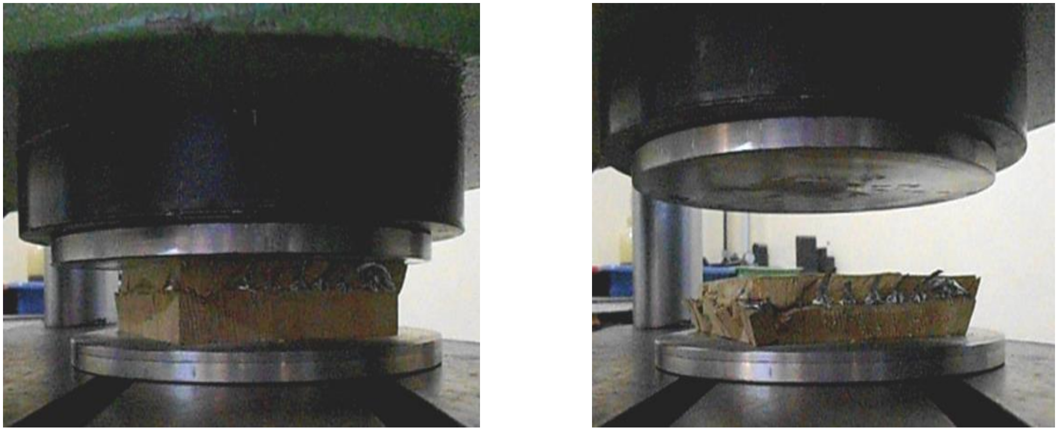
Stage I

Stage II



Stage III

Stage IV

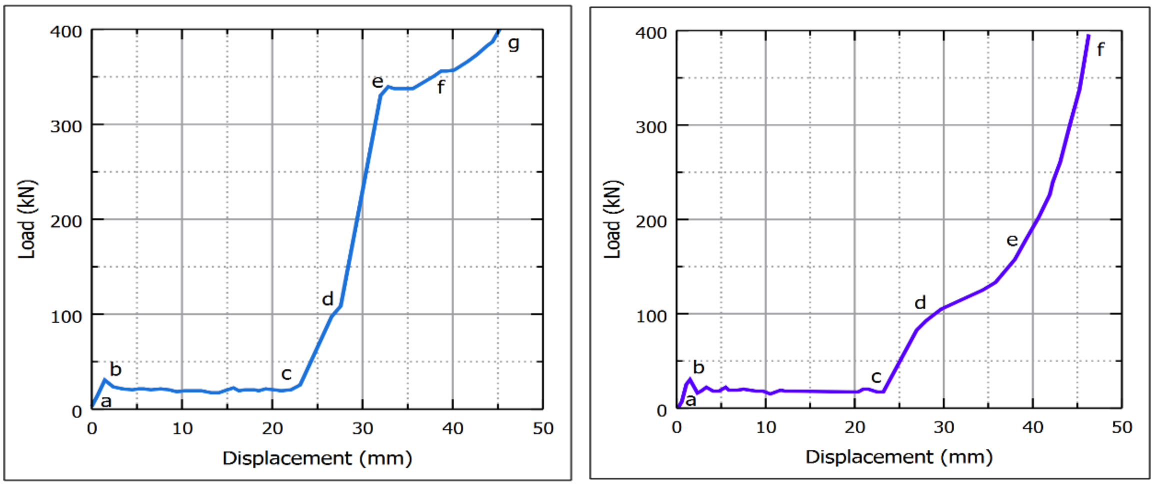


Stage V

Stage VI

Fig. 6 Quasi-Static compression of banyan-Aluminium honeycomb cellular sandwich panel (Type II) across the grain configuration (Stage I – Stage VI)

procedure where many micros die to puncture the cell walls of the wood. This phenomenon arises when a load is applied to a plateau region that is characterized by instability and a restricted range of deformation. The deformation persists as a whole entity, fully including the metallic plate in both



(a) (b)

Fig. 7 Load-Displacement curve for wood- aluminium honeycomb panel (a) Type I and (b) Type II

the wooden plates. The pace at which the load increases is considerably larger due to the rigid and robust response provided by both the cellular structure of wood and the solid inclusion, causing the material to become more rigid.

3.1 Deformation mechanism of Type I and Type II cellular sandwich panel

The Fig. 7 shows the load-displacement curve for wood-aluminum honeycomb panels. Aluminium honeycomb is placed between the wood specimens.

3.1.1 Elastic region of aluminium honeycomb (a-b):

Elastic deformation first occurs in the aluminum honeycomb core due to the distortion and elastic buckling of cell walls followed by the plastic collapse of layers of cell walls resulting in localized inelastic deformation at an applied load which is close to the initial crushing load. There is a significant decrease in load that distinguishes the elastic and plastic zones. A sharp reduction of load separates the elastic and plastic regions. Elastic and plastic characteristics are observed in the graph. Initially it was observed that only aluminium honeycomb undergoes compression under application of loads while wood remains unaffected.

3.1.2 Plateau region of aluminium honeycomb (b-c):

Crushing of the aluminium honeycomb was seen to initiate from the upper surface of the cell walls. The magnitudes of the little peaks, which indicate slow folding collapse, are initially higher and eventually diminish. The plastic collapse consistently took place at one end, often the top, and the deformation front steadily advanced as the crushing continued until the plastic deformation neared the bottom end of the specimen.

3.1.3 Densification region of aluminum honeycomb (c-d):

The load exhibited a significant and quick increase, which suggests the compaction of the aluminum honeycomb specimen. In Type I cellular sandwich panel, the graph shows that up to a

Table 2 Results of Type I panels

Panel	Weight in kg			Energy absorbed(J)	Specific energy absorbed (kJ/kg)
	Honeycomb	Wood	Sandwich Panel		
Panel 1	0.0221	0.096	0.118	6182.66	52.39
Panel 2	0.0230	0.095	0.118	6364.72	53.93
Panel 3	0.0224	0.091	0.113	6223.40	55.07
Panel 4	0.0222	0.094	0.116	6287.33	54.20

Table 3 Results of Type 2 panels

Panel	Weight in kg			Energy absorbed(J)	Specific energy absorbed (kJ/kg)
	Honeycomb	Wood	Sandwich Panel		
Panel 1	0.02	0.095	0.115	3485.23	30.30
Panel 2	0.02	0.098	0.118	3955.69	33.51
Panel 3	0.02	0.09	0.11	3908.09	36.19
Panel 4	0.02	0.093	0.113	3564.23	31.54

displacement of 23mm, aluminum honeycomb is crushed. Further 5mm displacement shows densification. In Type II cellular sandwich panel, the graph shows that up to a displacement of 24mm, aluminum honeycomb is crushed. Further 4mm displacement shows densification.

3.1.4 Crushing of wood (d-e-f-g):

In Type I crushing of wood begins and continues for the next 18mm. Wood started deforming at a load of 290 kN. Plastic buckling of wood panels occur. The area under the curve represents the amount of energy that has been absorbed and it is about 6364.726J (Table 2). In Type II, crushing of wood begins and continues for the next 19mm. After a load of 294kN densification of wood takes place. The deformation position ‘g’ won’t exist in Type II loading. The area under the curve represents the amount of energy that has been absorbed and it is about 3908.095J (Table 3).

3.2 Interpretation of the deformation behavior with application of Machine learning

In the present work, the linear regression model (LR) (Lee *et al.* 2016) are used to understand the deformation behavior of the Type I and Type II panels. The behavior is interpreted with the experimental values obtained during manual method. The development of these models is accomplished by Python programming.

Initially, the acquired experimental data obtained by manual method is divided into training and testing data sets. About 85% of the data was used to train the models, and 15% for testing. Afterward, the training set of data is used to build the regression model. On the other hand, the testing data set is utilized to assess the suitability of the trained model. Figure 8 shows the flowchart of linear regression model algorithms used in the present study.

Linear Regression (Suresh *et al.* 2020) is a fundamental technique in supervised learning that is employed to determine the correlation between a dependent variable (target) and a set of independent variables (features). It is extensively employed for predictive analysis and serves as the fundamental form of regression analysis.

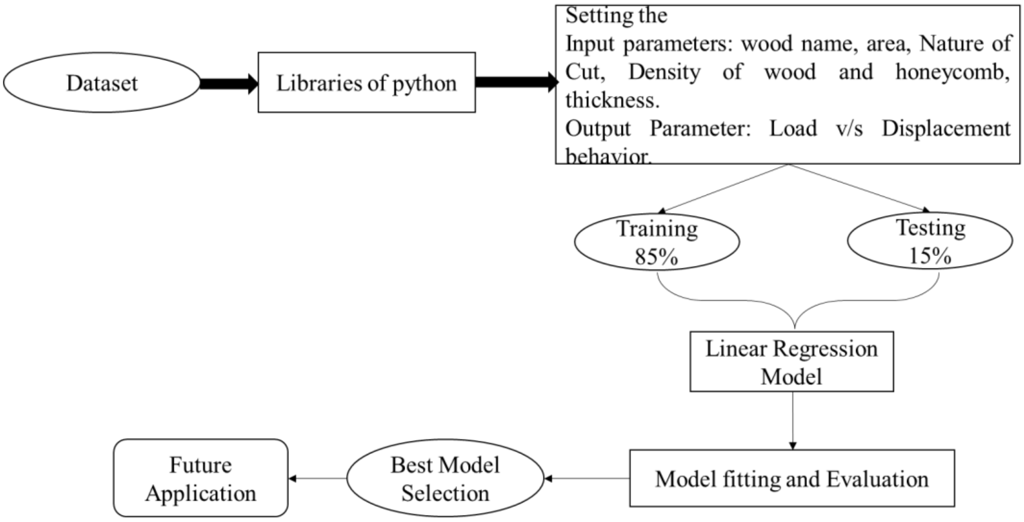


Fig. 8 Flow chart for prediction methodology

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \epsilon \qquad (1)$$

The dependent variable, shown as Y, is the variable that is being predicted or explained. The intercept of the line is represented by β_0, while β_1 refers to the linear regression coefficients. The variable X is the independent variable, which is utilized for predicting the dependent variable. Finally, the symbol ϵ denotes the error term, which encompasses the fluctuations in the dependent variable that are not accounted for by the independent variable.

Linear regression is a statistical method that establishes a straight-line relationship between input and output parameters. In this context, inputs are seen as independent variables, whilst the output is regarded as the dependent variable. Linear regression is a technique that determines a linear connection that accurately depicts the best fit of the model. Python modules are utilized to implement the linear regression model for the given data. The present study is conducted based on 66 datasets related to sandwich panels. Out of these 66, 33 datasets related to Type I panels and 33 related to Type II panels. The data is classified into input and output categories. The model accepts wood properties with aluminum panel as input, while energy behavior is treated as the output. The dataset is divided into a testing set, which comprises 15% of the data, and a training set, which comprises 85% of the data. Upon completing the training of the model, its accuracy is evaluated to determine its efficiency. This work considers the development and comparison of machine learning regression method LR model with traditional method to validate their accuracy in predicting stress strain curve (deformation behavior curve) and energy absorption.

3.3 Comparison between cellular sandwich panels of Type I and Type II

Fig. 9 shows the load v/s displacement curve for wood-aluminum honeycomb panels for 100*100*60 mm specimen. Aluminum honeycomb is placed between the wood specimens. Compression of the wood takes place in the radial direction. Here the crushing of the wood takes place due to the bending of the cell walls. At first, the cell walls on the surface layer bend uniformly

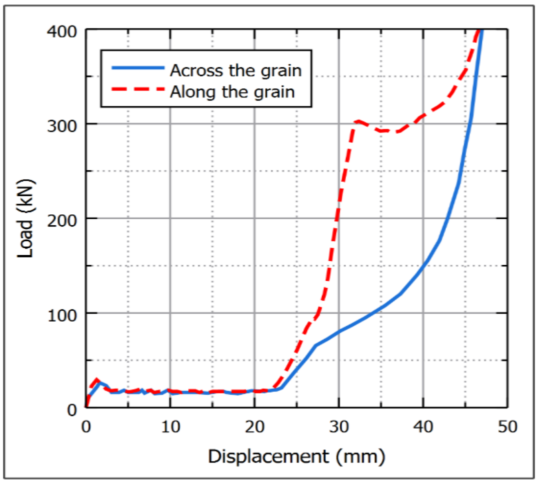


Fig. 9 Comparison of Load-Displacement curve for cellular panels

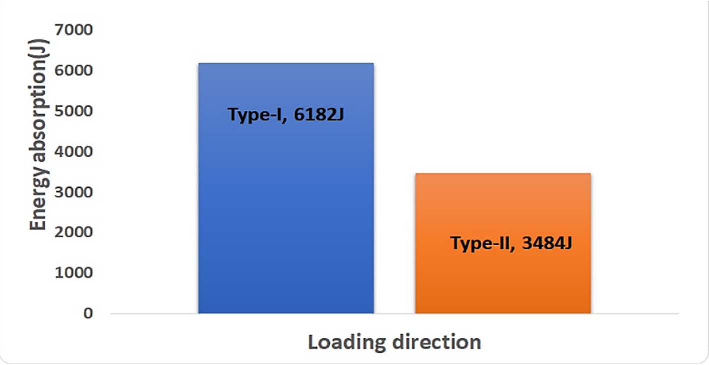


Fig. 10 Sample Comparison of energy absorption for Panel of Type Iand Type II

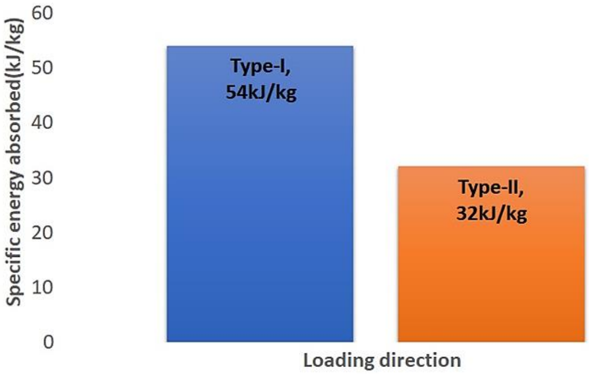
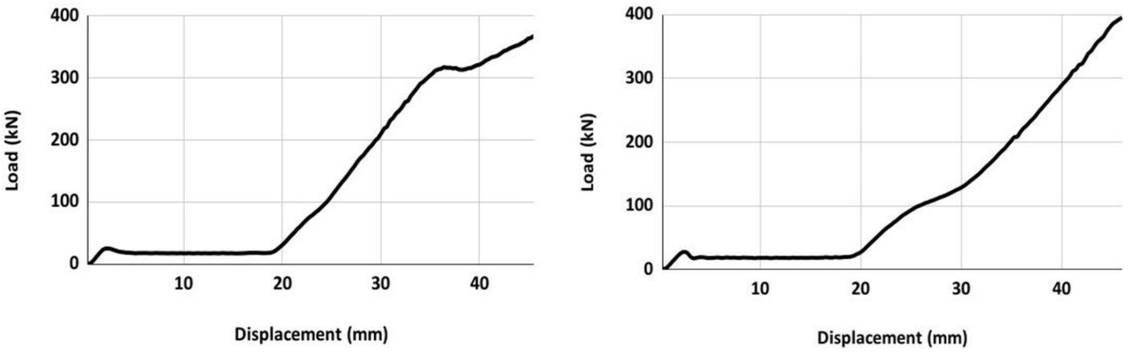


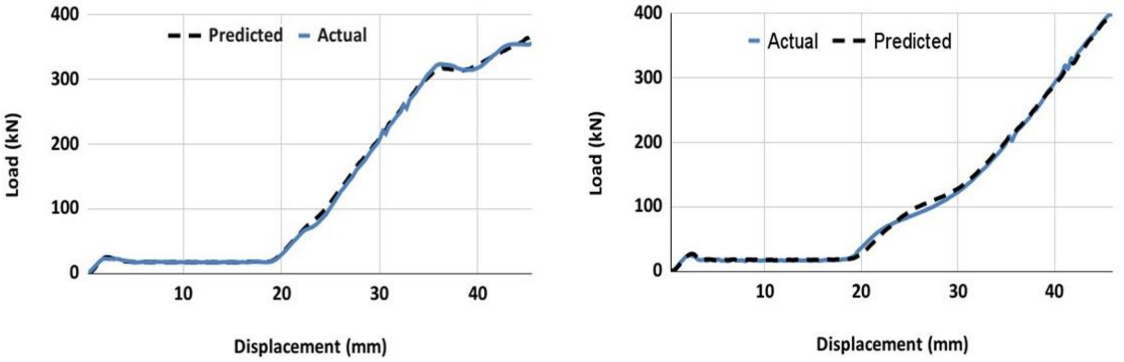
Fig. 11 Sample comparison of specific energy absorption for panel of Type I and Type II

and then this uniform crushing progressively continues through all the layers along the direction of the loading. The plastic collapse of the cells is not uniform, beginning at the surface of the loading plateau and spreading inward down the length of the specimen. Upon the completion of all the layers



(a) (b)

Fig. 12 Prediction model generated load v/s displacement curve for (a) Type I and (a) (b) Type II panels



(a) (b)

Fig. 13 Comparison of (a) Type I and (b) Type II panels behavior with respect to actual and predicted

are crushed completely the specimen begins to densify. It is the honeycomb structure which takes maximum amount of impact initially among the composite.

As seen from Fig. 9, the area under Type I curve (red line) is more than that of Type II (blue line). Therefore, energy absorption is more for along the grain configuration. The energy absorption for along the grain configuration (Type 1) is 6182.66 J, energy absorption for across the grain configuration (Type 2) is 3484.76 J (Fig. 10 and Fig. 11).

Application of machine learning model for prediction of deformation behavior (load vs displacement curve) the area under Type I and Type II, to compare the energy absorption with respect grain configuration. The model of linear regression shows the good fit (accuracy of 92%) of the Stress-strain curve with respect grain behavior. The model predicted behavior curve of the across the grains and along the grains are as shown in the Fig. 12.

The comparison of the experimental load-displacement behavior and model based load-displacement behavior for along the grain (Type-I) and across the grains (Type-II) are respectively shown as in Fig. 13.

The average correlation is found to be approximately 0.99 and the model can easily predict the load-displacement pattern or the energy absorption behavior for banyan -honeycomb panels for future application the prediction model has ability to provide the deformation behavior with mentioning the wood type. This will be having greater advantages to study have behavioral pattern of wood with respect to the grain behavior. The prediction models also have ability to predict any wood deformation behavior in addition of training for future applications. The results shows that the energy absorption of the along the cut grains are effective than the across the grain behavior. The future study is also concentrated based on different wood the variation energy absorption and study of impact energy absorption capacity with respect the variation of honeycomb panel thickness. The principal findings are summarized as follows.

- Type I panels demonstrated approximately 55 kJ/kg specific energy absorption, surpassing Type II, which exhibited around 36 kJ/kg.
- Experimental and predicted deformation behaviors exhibited over 99% correlation utilizing machine learning.
- The deformation mechanism progressed through sequential stages of elastic behavior, plastic plateau, densification, and wood fracture.
- Machine learning prediction facilitates the design of energy absorbers with reduced experimental expenses.

4. Conclusions

Series of studies were performed to investigate the behavior of cellular sandwich panels consisting of an aluminum honeycomb core and wood skin under quasi-static axial compression stress conditions. The tests were conducted as per ASTM standards. From the study the following conclusions were made: Aluminum honeycomb is a good energy absorbing material and hence it can be used as a core material for the sandwich panel to absorb energy. Wood crushed along the grain has more specific energy absorbing capacity than wood crushed across the grain. The sandwich panel in which wooden skins oriented along the grain configuration (Type I) absorbs more energy than that, in which the grains oriented across the grain (Type II). The specific energy absorption capacity obtained during investigation can be used as data in designing the energy absorbers for various engineering applications like crash pads and quasi-static test results can be taken as reference for dynamic behavior of the sandwich panels under impact loading conditions. The prediction model (LR) developed to interpret the energy absorption of panel shows close relationship between manual method of energy absorber. An average correlation of 0.99 was observed between experimental and predicted data. The model developed had the ability to recreate the deformation behavior for given panel and helpful for future application in selection of panels based on their energy absorption capacity.

Future research could expand the suggested machine learning framework by integrating a wider range of methods, including Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Random Forests. These models may provide enhanced prediction powers and resilience for intricate, nonlinear connections characteristic of material behavior. The model's usefulness can be expanded by assessing its performance under dynamic impact testing settings and using various material combinations, including bamboo-reinforced composites and foam cores.

References

Ciepielewski, R., Gieleta, R. and Miedzińska, D. (2022), "Experimental study on static and dynamic response of aluminum honeycomb sandwich structures", *Materials*, **15**(5), 1793. https://doi.org/10.3390/ma15051793.

Da Silva, A. and Kyriakides, S. (2007), “Compressive response and failure of balsa wood”, *Int. J. Solids. Struct*., **44**(25-26), 8685-8717. https://doi.org/10.1016/j.ijsolstr.2007.07.003.

De Naurois, C.J., Bourdin, C., Stratulat, A., Diaz, E. and Vercher, J.L. (2019), “Detection and prediction of driver drowsiness using artificial neural network models”, *Accid. Anal. Prev*., **126**, 95-104. https://doi.org/10.1016/j.aap.2017.11.038.

Dong, J., Li, W. and Fan, H. (2021), “Axial crushing behaviors of buckling induced triangular tubular structures”, *Mater. Des*., **201**, 109513. https://doi.org/10.1016/j.matdes.2021.109513.

Fathi, A., Wolff-Fabris, F., Altstädt, V. and Gätzi, R. (2013), “An investigation on the flexural properties of balsa and polymer foam core sandwich structures: Influence of core type and contour finishing options”, *J. Sandw. Struct. Mater*., **15**, 487-508. https://doi.org/10.1177/1099636213487004.

Gerhards, C.C. (1982), “Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects”, *Wood Fiber Sci*., **14**(1), 4-36.

Jiang, W., Zhang, Y., Han, H., Huang, Z., Li, Q. and Mu, J. (2024), “Mobile traffic prediction in consumer applications: a multimodal deep learning approach,” *IEEE T. Consum. Electron*, **70**(1), 3425-3435. https://doi.org/10.1109/TCE.2024.3361037.

Jiang, W., Han, H., Zhang, Y. and Mu, J. (2024), “Federated split learning for sequential data in satellite–terrestrial integrated networks”, *Inf. Fusion*, **103**, 102141. https://doi.org/10.1016/j.inffus.2023.102141.

Jiang, W., Han, H., He, M. and Gu, W. (2024), “ML-based pre-deployment SDN performance prediction with neural network boosting regression”, *Expert Syst. Appl*., **241,** 122774. https://doi.org/10.1016/j.eswa.2023.122774.

Lee, K.Y., Chung, N. and Hwang, S. (2016), “Application of an artificial neural network (ANN) model for predicting mosquito abundances in urban areas”, *Ecol. Inform*., **36**, 172-180. https://doi.org/10.1016/j.ecoinf.2015.08.011.

Lima, R.M., Ismarrubie, Z.N., Zainudin, E.S. and Tang, S.H. (2011), “Axial behavior of steel tube wrapped by composite as energy absorber under compressive load”, *ISBEIA 2011 - IEEE Symposium on Business, Engineering and Industrial Applications*, Langkawi, Malaysia September, 10-15. https://doi.org/10.1109/ISBEIA.2011.6088784.

Luger, G.F. (2009), *Artificial Intelligence: Structures and Strategies for Complex Problem Solving*, Pearson Education, Boston, U.S.A.

Papka, S.D. and Kyriakides, S. (1999), “Biaxial crushing of honeycombs: - Part 1: Experiments”, *Int. J. Solids. Struct*., **36**(29), 4367-4396. https://doi.org/10.1016/S0020-7683(98)00224-8.

Paravano, A. (2017), “Study of the behavior of honeycomb structures subjected to static and dynamic loads” Ph.D. Dissertation, University of Padova, Padua, Italy.

Rai, A. and Mitra, M. (2021), “Lamb wave based damage detection in metallic plates using multi-headed 1-dimensional convolutional neural network”, *Smart Mater. Struct*., **30**(3), 035010. https://doi.org/10.1088/1361-665X/abdd00.

Reddy, B.V., Sharma, K.V., and Reddy, T.Y. (2014), “Deformation and impact energy absorption of cellular sandwich panels”, *Mater. Des*., **61**, 217-227. https://doi.org/10.1016/j.matdes.2014.04.047.

Schreyer, H.L. and Zuo, Q.H. (1995), “Anisotropic plasticity model for foams and honeycombs”, *J. Eng. Mech*., **120**(9), 1913-1930. https://doi.org/10.1061/(ASCE)0733-9399(1994)120:9(1913).

Suresh, V., Janik, P., Rezmer, J. and Leonowicz, Z. (2020), “Forecasting solar PV output using convolutional neural networks with a sliding window algorithm”, *Energies*, **13**(3), 723. https://doi.org/10.3390/en13030723.

Upadhya, A., Thakur, M.S., Sharma, N., Almohammed, F.H., and Sihag, P. (2024), “A study of glass and carbon fibers in FRAC utilizing machine learning approach”, *Adv. Mater. Res*., **13**(1), 63-86. https://doi.org/10.12989/amr.2024.13.1.063

Usta, F., Türkmen, H.S. and Scarpa, F. (2021), “Low-velocity impact resistance of composite sandwich panels with various types of auxetic and non-auxetic core structures”, *Thin Walled Struct*., **163**, 107738. https://doi.org/10.1016/j.tws.2021.107738.

Wang, S., Zhang, M., Wang, Y., Huang, Z. and Fang, Y. (2021), “Experimental studies on quasi-static axial crushing of additively-manufactured PLA random honeycomb-filled double circular tubes”, *Compos.*

Struct., **261**, 113553. https://doi.org/10.1016/j.compstruct.2021.113553.

Wu, E. and Jiang, W.S. (1997), "Axial crush of metallic honeycombs", *Int. J. Impact Eng*., **19**(5-6), 439-456. https://doi.org/10.1016/s0734-743x(97)00004-3.

Yadav, S.S. and Chhapkhane, N.K. (2012), "Design and testing of lightweight sandwich t-joint of composite material using FEA and experimental technique", *Int. J. Eng. Res. Technol*., **1**(6), 2278-0181. https://doi.org/10.17577/IJERTV1IS6341.

Zhang, J. and Ashby, M. F. (1994), "Mechanical selection of foams and honeycombs used for packaging and energy absorption", *J. Mater. Sci*., **29**(1), 157-163. https://doi.org/10.1007/BF00356587.

Zhu, Y. and Sun, Y. (2021), "Low-velocity impact response of multilayer foam core sandwich panels with composite face sheets", *Int. J. Mech. Sci*., **209**, 106704. https://doi.org/10.1016/j.ijmecsci.2021.106704.

CC