Bio-Inspired Composite Sandwich Beam Model Subjected to Low Velocity Impact

Koh Wee Kiam, Ahmad Kueh Beng Hong

Faculty of Civil Engineering, Universiti Teknologi Malaysia, Malaysia

kbhahmad@utm.my

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Abstract. This study is about impact damages for bio-inspired composite sandwich beam subjected to low velocity impact by using spring-damper-mass model. This model is able to predict the damage behaviour of composite sandwich structure in a rapid fashion. The composite sandwich beam model is made up of 3 plies of carbon fibre reinforced polymer (CFRP) with mirror orientation for top and bottom skins, which separated by Nitrile Butadiene Rubber (NBR) core and aluminium honeycomb core. This sandwich beam model is inspired by mechanical analysis of woodpecker drumming and its application to shock-absorbing systems by Yoon and Park [1]. Spring-damper-mass model is created using MATLAB and verified by using Finite Element Analysis software, ABAQUS. The deflections and absorbed energy of the composite sandwich beam model have been determined. On the other hand, Genetic Algorithm (GA) optimisation also has been carried out to obtain the best performing sandwich beam model in order to maximize the absorbed energy per mass and minimize the Tsai-Hill failure criteria of top skin of composite sandwich beam model. It was found that the best angle of fibre orientation for skin is 0° for impact energies of 2.73J, 5J and 8J. Meanwhile, the best honeycomb core thickness is 5mm for impact energies of 2.73J and 5J, but it increases to become 9.04mm when the applied impact energy is 8J.

Introduction

Composite sandwich materials are rapidly developed and widely used in civil engineering fields due to their advanced features compared to conventional structural constructions. However, there are still unchangeable fact that composite sandwich material has its own weakness. Hence, composite materials are often tested to prevent failures. In this context, collapse of the World Trade Center on September 11, 2001 because two jet airlines struck the building, which cause 2752 people died reported by Broughton [2] alert the researchers about the importance to ensure structure is safe to withstand sudden impact. Spring mass model is one of the methods to predict the impact responses of composite sandwich structure with a much simple way. There is a great study about mechanical analysis of woodpecker drumming by Yoon and Park [1], where the researchers suggest a bio-inspired shock absorbing system. Hence, the intention of this study is to explore the most performing composite sandwich material from the proposed design and fabrication of bio-inspired shock-absorbing system.

Besides, extent of seriousness of damage in the composite sandwich structure is difficult to determine through naked eyes.[3-5] And the common found finite element analysis also requires detailed simulation technique in order to solve a simple problem. [6] So, this study aims to formulate the spring-damper-mass model inspired by the woodpecker's head configuration and produce MATLAB coding for the behaviour of the model. And, this study also carries out optimisation for the best performing sandwich beam model in terms of impact behaviour. From the created spring-damper-mass model, a raw picture of damage behaviour of composite sandwich structure in shorter time and lesser cost. However, there are boundaries for this study as stated below:

1. This study only focuses on the simulation for the beam structures using spring mass modelling.
2. The skins are only made up of 3 plies of carbon fibre reinforced polymer (CFRP) with mirror orientation for top and bottom skins.
3. This beam model only contains two different cores, which are Nitrile Butadiene Rubber (NBR) core and aluminium honeycomb core.
4. MATLAB is the only software used as programming language.
5. Only low velocity impact response is considered.
6. Only single point load at centre of beam model is considered.
7. Only semi-rigid supported boundary condition is considered.
8. Only large mass problem is considered.
9. Only Genetic Algorithm (GA) is used for optimisation.

Previous Studies

From previous studies, there are different types of theories developed and utilised for the composite sandwich material studies. [7-11] Basically, composite sandwich structures contain two thin yet stiff skins separated by a lightweight but low modulus thick core [6]. The skins are usually fabricated by one or more lamina/ply stacked together using matrix material such as resin. [12] A study conducted by Maher, Ramadan [13] mentioned that the changes in ply orientations are able to influence damping capacity of composite structure. In this paper, the result showed that the angle of fibre orientations of the outer laminate have significant effects compared with the inner laminate.

Besides, there are a lot of materials can be utilised as the core for sandwich structures. [14] Honeycomb cores, which were developed since 1940's in aerospace industry also widely used in composite material studies. [12, 15-23] One of the studies about the strength characteristics of aluminium honeycomb sandwich panels done by Paik, Thayamballi [17] also stated that increase of thickness of honeycomb core results in a higher ultimate strength. On the other hand, rubber is a common vibration damping material, which is always used as core for the composite sandwich material due to its viscoelasticity. However, weakness of rubber in the perspective of stiffness results in a rather low value of the loss modulus. [24] Cores made of honeycomb and solid viscoelastic materials studied previously also make use of their unique properties to meet the design criteria. In a study done by Li [15], the honeycomb material is used to increase the stiffness of the entire structure while the foam improves the damping of the structure. This was unsuccessful because the trade-off between the overall stiffness and the sound transmission properties occurred in the design stage. However, this inspires the readers to further the study using composite sandwich structure with two cores.

Moreover, researchers also discuss about the type of impact applied to the composite sandwich material before evaluation for its impact behaviour. [4, 25] Impact duration is too difficult to obtain as it depends on the medium where it travels. Hence, type of impact is usually determined based on the velocity of loading. In this review paper, impact mass is another consideration to determine the type of impact rather than velocity of loading.[6] The responses of large and small mass impacts show that large mass impact is basically boundary-controlled impact while small mass impact is wave-controlled impact. Analysis for small mass impact usually requires dynamic motion basics whereas equivalent dynamic mass of the structure in large mass impact may be neglected. [26]

There are various analytical method for the impact response, including spring-mass model, superposition method, energy balanced method and finite element simulation approach.[6] Spring mass model is the easiest approach to determine the contact force between the impactor and the composite sandwich structure. In a study done by Anderson [27] to investigate the single degree-of-freedom models for large mass impact on sandwich composite also revealed that non-linear spring-mass model was sufficient to characterize the elastic impact event.

Based on previous studies, it is shown that not many researches about composite sandwich structure with two cores can be found. Therefore, this work will focus on the 4-layered composite sandwich structure as inspired from endoskeletal structure of woodpecker from study by Yoon and Park [1] subjected to low velocity impact. And this paper will apply spring-damper-mass model to predict the impact response of desired composite sandwich structure. This is because although finite element simulations can provide more accurate result, the process of analysis consume a lot of time and can be sometimes expensive. Important time-based information like internal stresses and strains are thus difficult to capture [6].

Problem Formulation

The composite sandwich beam model is inspired from the research done by Yoon and Park [1]. The shock absorbing mechanism of woodpecker's head give rise to this concept design. Figure 1 illustrate the endoskeletal structure of woodpecker's head and composite sandwich beam model in this study.

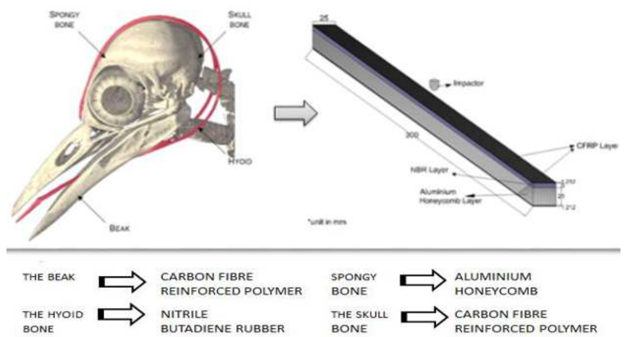


Figure 1: Endoskeletal structure of woodpecker's head and composite sandwich beam model

The skins are made up of carbon fibre reinforced polymers (CFRP), which act as harder external layer like the beak and skull bone of woodpecker. Then, the viscoelastic hyoid bone and porous spongy bone of woodpecker is further inspired the use of Nitrile Butadiene Rubber and aluminium honeycomb as core in this beam model. And the physical properties of sandwich materials modelling are determined through measured values from experimental approach and recorded in Tables 1, 2 and 3, respectively.

Table 1: Properties of the skins

Properties	Details
Material	Mapewrap C-Uni AxHM Carbon Fibre Reinforced Polymer mix with Epicote 1006 (CFRP/ epoxy)
Top Skin Fiber Orientation	[0/-Ө/Ө]
Bottom Skin Fiber Orientation	[Ө /-Ө/0]
Number of ply	3
Angle of fibre orientation	30°
Ply Thickness, t_f	0.404mm
Density	998.34 kg/m^3
Longitudinal Extensional Modulus, E_1	45839.11MPa
Transverse Extensional Modulus, E_2	2369.9 MPa
Poisson ratio, v_{12}	0.319
In-plane shear modulus, G_{12}	4313.887334 MPa
Maximum Longitudinal Stress	752.2013MPa
Maximum Transverse Stress	4.29024MPa
Maximum Shear Stress	270MPa

Table 2: Properties of first core

Properties	Details
Material	Nitrile Butadiene Rubber (NBR)
Thickness of Layer	3mm
Density	1200kg/m^3
Extensional Modulus, E	25.26 MPa
Poisson ratio, v_{12}	0.49

Table 3: Properties of discretized element for second core

Properties	Details
Material	Aluminium Honeycomb
Geometry	Hexagonal
Thickness of Layer	20mm
Thickness of Wall	0.1mm
Density	83.46kg/m^3
Cell Size	5mm
Extensional Modulus of honeycomb, E_m	69000 MPa
Poisson ratio of honeycomb, v_m	0.33

In the simulation, vertical low velocity impact is applied on the sandwich model. The impact is modelled as hemisphere steel bullet hits vertically on the top skin of composite sandwich beam model. The details for the impactor are shown in the Table 4.

Table 4: Properties of Impactor

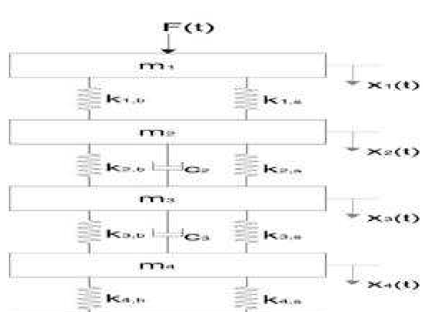
Properties	Details
Geometry	Hemisphere-ended Cylinder
Drop Height	1m
Velocity	1.03m/s
Mass	5.131kg
Impact Duration	0.01445s
Incident Energy	2.73J

By using Lagrange equation of motion as shown below, the dynamic analysis of this spring-damper-mass model is conducted to evaluate its impact damages.

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{1}$$

where m is the mass, c is the damping coefficient, k is the stiffness and x is the displacement of the mass in matrix form.

A spring-damper-mass model is prepared to identify the impact behaviours of the composite sandwich beam model. In this model, 4 degree-of-freedom motion for the whole composite sandwich beam model is shown in the Figure 2. Damping properties of the skin layers is negligible in this work as the thin layer of skins does not enhance the shock absorbing mechanisms of the structure.



Subscripts
1. CFRP Top Skin Layer
2. Nitrile Butadiene Rubber Core Layer
3. Aluminium Honeycomb Core Layer
4. CFRP Bottom Skin Layer

Figure 2: Spring-damper-mass model of composite sandwich beam model

Figure below illustrates the simulation process of spring-damper-mass beam model in this work.

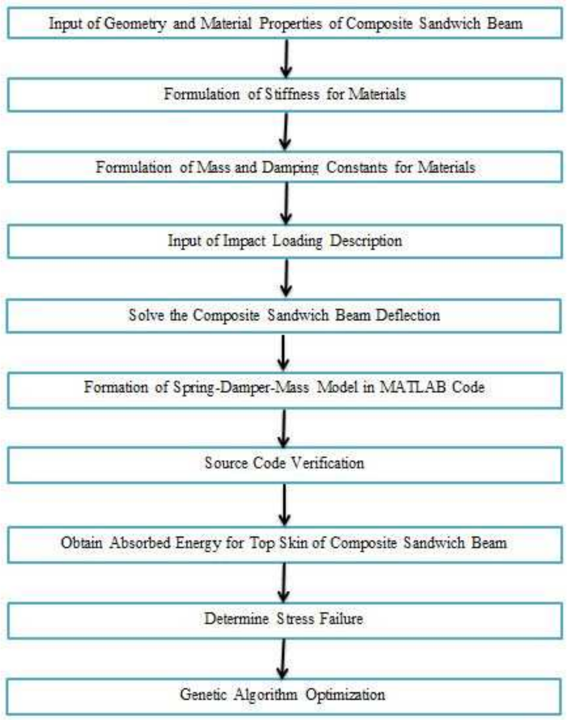


Figure 3: Spring-damper-mass beam model simulation process

Formulation of Stiffness for Materials

Stiffness of materials is obtained through the formulation for large mass impact response as stated in the scientific report by Olsson [26]. For a semi-rigid supported composite sandwich beam model with side length 2A in the x-direction and 2B in the y-direction, the bending stiffness is determined using Equation 2 with multiplication coefficient of 59.

$$k_b = 59\frac{59\sqrt{D^*D_{22}\sqrt{\eta+1}}/2}{(2B)^2} \qquad \text{for } \bar{A} = \frac{A}{B} \geq 3 \tag{2}$$

On the other hand, the shear stiffness for a beam subjected to point load at centre of beam in semi-rigid supported boundary condition is calculated by using equations below. Likewise, it has multiplication coefficient of 1.75 to modify the equations found in scientific report by Olsson [26].

$$k_s = 1.75 \times S^* 1.467\left(1 + \frac{\bar{A}}{10.12}\right) \tag{3}$$

In the spring-damper-mass model, equivalent stiffness due to bending and shear stiffness of the beam is utilised. It is obtained from the Equation 4.

$$\frac{1}{k_{bs}} = \frac{1}{k_b} + \frac{1}{k_s} \tag{4}$$

Formulation of Mass and Damping Constants for Materials

Another constant in Lagrange equation is the mass and damping constant. It can be determined by using Equations 5 and 6, respectively.

$$\mathrm{m} = \rho \times \mathrm{V} \tag{5}$$

$$c = \tan\delta\sqrt{m \times k} \quad (6)$$

where m is the mass, ρ is the density, V is the volume of material and tan δ is the damping ratio.

Formulation of Impact Force

From the study of Williamson [23], the impact force, F(t), is approximate using Equation 7.

$$F(t) = \frac{m v_o \pi}{t_o} \sin \frac{\pi t}{t_o}. \quad (7)$$

where

m is the mass of impactor,

v_o is the velocity of impactor hits the composite sandwich beam model,

t_o is the duration of impact of the composite sandwich beam model,

t is the time interval.

Formulation of the Deflection for Composite Sandwich Beam Model

All constants for spring-damper-mass model are then assembled into a proper form as below:

$$\begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix} \begin{bmatrix} \ddot{x_1} \\ \ddot{x_2} \\ \ddot{x_3} \\ \ddot{x_4} \end{bmatrix} + \begin{bmatrix} c_1 & -c_1 & 0 & 0 \\ -c_1 & c_1 + c_2 & -c_2 & 0 \\ 0 & -c_2 & c_2 + c_3 & -c_3 \\ 0 & 0 & -c_3 & c_3 + c_4 \end{bmatrix} \begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{bmatrix} + \begin{bmatrix} k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2 + k_3 & -k_3 \\ 0 & 0 & -k_3 & k_3 + k_4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} F(t) \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (8)$$

where the subscripts 1, 2, 3 and 4 represent the top skin, first core, second core and bottom skin, respectively.

Then, the displacement of spring-damper-mass model, which is the deflection for composite sandwich beam model is calculated according to the Newmark Method as shown in Equations 9 to 13.

$$K_{eff} = K_{sandwich} + a_o M_{sandwich} + a_1 C_{sandwich} \quad (9)$$

$$F_{eff} = F_{sandwich}^{t+\Delta t} + M_{sandwich}(a_o x_t + a_2 \dot{x}_t + a_3 \ddot{x}_t) \quad (10)$$

$$C_{sandwich}(a_1 x_t + a_4 \dot{x}_t + a_5 \ddot{x}_t) \quad (11)$$

$$x_{t+\Delta t} = \frac{F_{eff}}{K_{eff}} \quad (12)$$

$$\ddot{x}_{t+\Delta t} = a_o(x_{t+\Delta t} - x_t) - a_2 \dot{x}_t - a_3 \ddot{x}_t \quad (13)$$

where

K_{eff} is the effective stiffness,

F_{eff} is the effective force,

u is the displacement of the composite sandwich plate,

$\dot{u}$ is the velocity of the composite sandwich plate,

$\ddot{u}$ is the acceleration of the composite sandwich plate,

Δt is the time step and,

a_o, a_2, a_3, a_4, a_5, a_6 and a_7 are the integration constants.

γ and β are the integration parameters selected as 0.5 and 8.5 , respectively.

In addition, the area under the graph of force against deflection is utilised to obtain the energy using trapezoidal numerical integration using MATLAB.

Formulation of the Stress Failure of Composite Sandwich Beam Model

The global and local strain at each layer can be calculated using Equation 14 and Equation 15, respectively.

$$\{\epsilon\}_{x,y} = \{\epsilon^o\} + z\{k\} \tag{14}$$

$$\{\epsilon\}_{1,2} = [T]^{-T}\{\epsilon\}_{x,y} \tag{15}$$

where

ϵ^o is the mid-plane strain,

k is the mid-plane curvatures,

Next, local stress of the composite sandwich is obtained by multiply the local strain with the stiffness matrix as shown in Equation 16.

$$\{\sigma\}_{1,2} = [Q]\{\epsilon\}_{1,2} \tag{16}$$

Lastly, stress failure is determined using Tsai-Hill criterion, which is the extension to Hill's anisotropic study.[28] And the general expression of this failure criterion is indicated as Equation 17.

$$\left(\frac{\sigma_1}{\sigma_L}\right)^2 - \frac{\sigma_1 . \sigma_2}{{\sigma_L}^2} + \left(\frac{\sigma_2}{\sigma_T}\right)^2 + \left(\frac{\tau_{12}}{\tau_{max}}\right)^2 \geq 1 \tag{17}$$

where

σ_L is the maximum longitudinal stress of layer,

σ_T is the maximum transverse stress of layer,

τ_{max} is the maximum shear stress of layer.

Formulation of the Objective Functions for Optimisation

In this extend, MATLAB built-in toolbox, which is known as the Genetic Algorithm is utilised in order to conduct optimisation process in determine the best performing composite sandwich beam. The optimisation problems for absorbed energy per mass and Tsai-Hill failure criteria, $\bar{s}$ for top skins of composite sandwich beam model are formulated as follows:

$$\text{Minimize } -\bar{E} = -(p_{00} + p_{10}x + p_{01}y + p_{11}xy + p_{02}y^2 + p_{12}xy^2 + p_{03}y^3 + p_{13}xy^3 + p_{04}y^4) \tag{18}$$

$$\text{Minimize } \bar{s} = q_{00} + q_{10}x + q_{01}y + q_{20}x^2 + q_{11}xy + q_{02}y^2 + q_{30}x^3 + q_{21}x^2y + q_{12}xy^2 + q_{03}y^3 + q_{40}x^4 + q_{31}x^3y + q_{22}x^2y^2 + q_{13}xy^3 + q_{04}y^3 + q_{50}x^5 + q_{41}x^4y + q_{32}x^3y^2 + q_{23}x^2y^3 + q_{14}xy^4 \tag{19}$$

Here, p_{ij} and q_{ij} are the coefficients of the polynomial, x is the angle of fibre orientation of the CFRP layer and y is the aluminium core thickness.

Results and Discussion

Material Characteristics

The MATLAB source code is verified to ABAQUS model. Basically, the inputs for both approaches are matched and the top skin deflection is compared.

From the two models, graph of top skin deflection against time is plotted as shown in Figure 4. The maximum deflection of the top skin of ABAQUS model happened at 0.007225s, which is 4.164mm. Meanwhile, the spring-damper-mass model has the maximum deflection of 4.108mm for its top skin at 0.007395s. The difference of maximum deflection and the time for both models to experience maximum deflection are 1.35% and 2.33%, respectively. Hence, it is indicated that the outcome from both models do not have much difference and thus, this source code is accepted to conduct analysis on another kind of 4 layered composite sandwich structures.

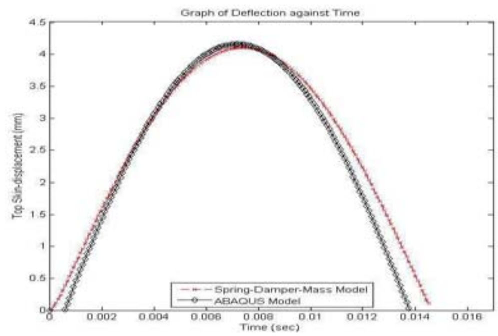


Figure 4: Graph of top skin deflection against time

Deflection of Composite Sandwich Beam Model

In this spring-damper-mass model, it is made up of 2 cores, which are Nitrile Butadiene Rubber (NBR) core and aluminium honeycomb core. The deflection of each layer is shown in Figure 5. From the graph, it is shown that the deflection of aluminium honeycomb core and bottom skin have less and almost zero displacement. It is due to presence of NBR as viscoelastic layer before the honeycomb core layer to distribute the impact evenly and reduce the impact damage to the following layers. The maximum deflection of top skin and NBR layer is 4.108mm while honeycomb core and bottom skin have only 0.007mm and 0.000mm deflection, respectively.

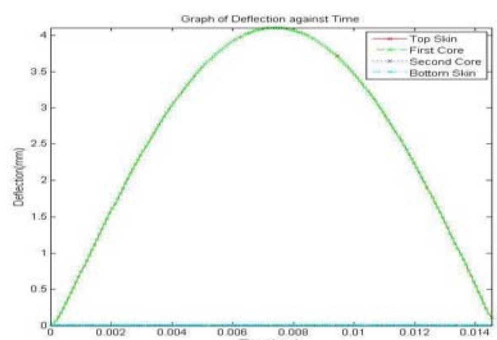


Figure 5: Graph of deflection against time

Regarding deflection of composite sandwich beam model, it is basically relied on stiffness of the beam model and the applied force. If the beam model is enough stiff, then the deflection will be smaller. In this study, the effective stiffness of each layer for the composite sandwich beam model is indicated in Table 5. It is clearly shows that the effective stiffness of NBR layer is much lower than the other layer of the beam model. Therefore, NBR layer tends to deflect as much as the deflection of outer skin because NBR itself cannot withstand the impact. However, the stiffer underneath honeycomb core and bottom skin does not been affected.

Table 5: Effective stiffness of each layer for the composite sandwich beam model

Layer	Material	Effective Stiffness (N/m)
Top Skin	CFRP/epoxy	9.9378e+06
First Core	NBR	279.8773
Second Core	Aluminium Honeycomb	1.6472e+05
Bottom Skin	CFRP/epoxy	9.9378e+06

Absorption Energy of Composite Sandwich Beam Model. Absorbed energy of composite sandwich beam model can be determined at the end of impact incident from graph of energy against time as shown in Figure 6. It is obviously shows that the maximum impact energy is reducing when going down the layers of composite sandwich beam model.

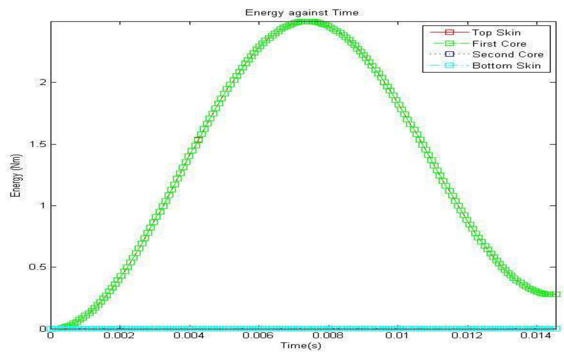


Figure 6: Graph of energy against time

The absorbed energy is then determined at the end of incident, which is known as the retained impact energy at each layer after impact incident. The absorbed energies of the top skin, first core, second core and bottom skin are 0.2789J, 0.2789J, 0.0005 and 0.0000J, respectively. It can be said that the absorbed energy of each layer is about 10% of the maximum impact energy applied to it. In this study, higher absorbed energy of the top skin is hoped to acquire in order to reduce the impact damage to the following layers as well as structure underneath.

Genetic Algorithm Optimisation Results

Unlike classical algorithm, GA generates a population of points, which approaches an optimal solution at each iteration. In order to determine the best angle of fibre orientation for skin and honeycomb core thickness, impact performance ratio is established as shown in Equation 20 to determine the maximum absorbed energy per mass and minimum value of Tsai-Hill failure criteria for top skin. The higher the impact performance ratio means higher absorbed energy compare to lighter mass and lower risk of stress failure for composite sandwich beam model. The optimisation parameters and outputs as well as the impact performance ratio are then gathered for comparison in Table 6.

$$\text{Impact Performance Ratio } = \frac{\text{Absorbed Energy per Mass}, \bar{E}}{\text{Tsai} - \text{Hill Failure Criteria}, \bar{s}} \times \frac{1}{Lg} \tag{20}$$

where

L is the length of composite sandwich beam model,

g is the gravitational acceleration.

Table 6: Genetic algorithm optimisation parameters and outputs as well as impact performance ratio

Angle of fibre orientation, ϑ	Honeycomb Core Thickness, h_2 (mm)	Absorbed Energy per Mass, $\overline{E}$(m^2s^{-2})	Tsai-Hill Failure Criteria, $\overline{s}$	Impact Performance Ratio
0.00	5.00	6.6156	2.2625	0.9936
0.52	9.07	5.7364	2.0489	0.9513
0.79	10.66	5.5183	-13.8213	-0.1357
0.59	10.07	5.5941	-7.7689	-0.2447
0.00	5.00	6.6156	2.2625	0.9936
1.15	11.18	5.4582	-18.6223	-0.0996
0.27	12.50	5.3245	-33.8017	-0.0535
1.17	13.93	5.2050	-43.4455	-0.0407
0.57	9.38	5.6905	-0.7515	-2.5731
0.82	11.87	5.3854	-26.6023	-0.0688
1.29	16.12	5.0567	-50.5820	-0.0340

However, the fitting for Tsai-Hill failure criteria tends to obtain negative value. In fact, it is impossible the failure criteria less than zero, therefore the outcomes for negative Tsai-Hill failure criteria are eliminated. And the parameters that have higher impact performance ratio are chosen as the best configuration from the series of outcomes from GA optimisation.

Besides the two objective functions mentioned early, optimisation also has been carried out using different impact energies to observe the influence to the output of optimisation. Table 7 and 8 show the results from optimisation using impact energies of 5J and 8J, respectively.

Table 7: Results from optimisation using 5J of Impact Energy

Angle of fibre orientation, ϑ	Honeycomb Core Thickness, h_2 (mm)	Absorbed Energy per Mass, $\overline{E}$ (m^2s^{-2})	Tsai-Hill Failure Criteria, $\overline{s}$	Impact Performance Ratio
0.00	5.00	12.1496	4.0125	1.0289
1.48	16.26	9.2677	-94.8897	-0.0332
0.76	12.85	9.7187	-67.2209	-0.0491
0.44	9.03	10.5462	3.8491	0.9310
1.06	13.38	9.6357	-74.2562	-0.0441
0.18	10.73	10.1175	-29.5582	-0.1163
1.25	12.11	9.8442	-52.3790	-0.0639
0.00	5.00	12.1496	4.0125	1.0289
1.04	11.41	9.9764	-39.8827	-0.0850
1.31	14.62	9.4624	-87.9203	-0.0366
1.35	10.37	10.1991	-17.9900	-0.1926

Table 8: Results from optimisation using 8J of Impact Energy

Angle of fibre orientation, ϑ	Honeycomb Core Thickness, h_2 (mm)	Absorbed Energy per Mass, $\overline{E}$(m^2s^{-2})	Tsai-Hill Failure Criteria, $\overline{s}$	Impact Performance Ratio
0.03	9.04	-16.8739	5.2503	1.0921
0.00	5.00	-19.4419	6.6608	0.9918
0.71	10.36	-16.3271	-31.5900	-0.1756
0.74	12.30	-15.6995	-91.7554	-0.0581
0.38	11.25	-16.0154	-62.0916	-0.0876
1.26	14.39	-15.1942	-135.7259	-0.0380
0.61	11.44	-15.9562	-66.5761	-0.0814
0.18	13.06	-15.5011	-114.2070	-0.0461
0.77	12.10	-15.7565	-85.7505	-0.0624
1.38	16.19	-14.8453	-149.6739	-0.0337
0.11	10.60	-16.2380	-42.5317	-0.1297

From these results, the optimum angle of fibre orientation for skin is 0° and the best honeycomb core thickness is 5mm for impact energies of 2.73J and 5J, respectively and increases to 9mm for 8J of impact energy. However, the results are different every time running of GA optimisation even the options of optimisation do not changed. Basically, it is due to GA starts with a random initial population, which is created by MATLAB random number generators. Every time a random number is generated, the state of the random number generators changed to produce different next generation.

Conclusion

The followings are the conclusion that can be drawn from this study:

5. The spring-damper-mass model is created by taking inspiration from the endoskeletal structure of woodpecker's head.
6. The MATLAB source code for composite sandwich beam model under low velocity impact is written.
7. The MATLAB source code is verified through comparison with the ABAQUS model outcomes.
8. Genetic Algorithm (GA) optimisation is formulated to maximize the absorbed energy per mass and minimize the Tsai-Hill failure criteria of the top skin for composite sandwich beam model.
9. The best angle of fibre orientation for skin is 0° for impact energies of 2.73J, 5J and 8J.
10. The best honeycomb core thicknesses are 5mm for impact energies of 2.73J, and 5J, but it increases to become 9.04mm when the applied impact energy is 8J.

And, there are few recommendations for the future studies from this study as stated below:

1. The spring-damper-mass model should be modified so that impact analysis is not restricted only for 4-layer composite sandwich beam.
2. Impact damages of composite sandwich structures should be considered buckling damage, matrix cracks, facing yielding, face wrinkling, core failure and core indentation as well as delamination problems.
3. More variables including CFRP ply thickness, NBR core thickness and cell wall angles of aluminium honeycomb core should be considered.
4. Nonlinear constraints should be established in order to have more precise values of output from Genetic Algorithm optimisation.
5. Graphical user interface (GUI) should be programmed to ease users.

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