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LOW-VELOCITY IMPACT OF COMPOSITE SANDWICH PLATE WITH FACESHEET INDENTATION DESCRIPTION

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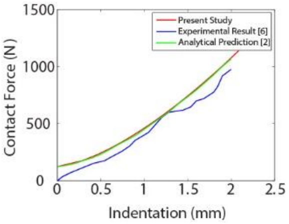
Graphical abstract



Abstract

Composite sandwich structures are applied in many engineering fields due to their high strength and stiffness but lightweight properties. There are currently not many studies that simultaneously consider both indentation and strain failure in the composite sandwich plate especially in presence of impact loading. Such knowledge is necessary to determine the facesheet strain after impact in order to find out whether the facesheet is totally failed as a result of indentation deformation. Hence, the purpose of this study is to model numerically the top facesheet indentation and strain failure of a fixed-end composite sandwich plate with honeycomb core when it is subjected to low-velocity impact at the center. The faceheets are made from Hercules AW193-PW prepreg consisting of AS4 fibers in a 3501-6 matrix (carbon/epoxy) with a stacking sequence of [0/90]. The honeycomb core is made from HRH 10 1/8-3.0 Nomex honeycomb (Ciba-Geigy). Type of the impactor used in this study is flat-ended cylinder, which is made from case-hardened steel. The composite sandwich plate is modeled as a two-dimensional problem with five and three degrees of freedom per node for the facesheets and honeycomb core, respectively. Only the stiffness matrix, [*K*], and the mass matrix, [*M*], are considered in determining the responses of the plate. Responses in terms of indentation, strain failure and displacement are explored for various facesheet and core properties. It is found that an increase in number of ply and ply thickness reduce the indentation on the top facesheet. Also, the most effective parameter in improving the strain failure of the top facesheet is the crushing resistance of the core.

Keywords: Composite sandwich plate, honeycomb core, low-velocity impact, indentation, strain failure

1.0 INTRODUCTION

Composite sandwich structures are widely explored and applied in numerous engineering fields, attributing to their favorable properties such as high strength and stiffness as well as reduced unit mass [1, 2]. A composite sandwich structure consists of two facesheets that are separated by a core. The facesheets are also known as composite skins. The facesheets and core component are commonly bonded by matrix materials such as resin. The core layer is usually made of lightweight and thick but less stiff materials, such as Nomex honeycomb cores, fiberglass reinforced thermoplastic, aluminum and foam-type cores. The top and bottom facesheets are commonly thin but stiff material from light alloys, e.g., aluminum and fiber-reinforced composites [3].

The composite sandwich structure may expose to several impact loading such as low-velocity impact, high-velocity impact, repeated impact, etc. Indentation can occur during construction and maintenance of the structure. For example, the composite sandwich structure may experience indentation due to the low-velocity impacts of tools drop, machineries mishandling, heavy materials falls and so on [4].

Thanks to many attractive structure properties, the use of composite sandwich structure is very beneficial in engineering field especially in civil, marine, aircraft and aerospace industries. As a product, its application helps in terms of cost effectiveness and environmental friendliness. For example, a vehicle fabricated from lightweight structures will require less energy to move and indirectly consume less fuel. This means that the use of lightweight vehicle will reduce environmental impact as well as service cost of the vehicle. In construction field, the application of composite sandwich structure is widely used in the lightweight construction.

Thus far, there are many studies regarding the modeling of composite sandwich plate and its analyses. One of the researches was performed by Meidell [5], which investigates the sandwich beams with honeycomb core by considering the minimum weight design. In this paper, the constitutive core equations were formulated. The core formulation was found with errors less than 0.25% and 1% of any volume fraction for effective longitudinal shear modulus and effective transversal Young's modulus, respectively. Abdolrahim *et al*. [6] carried out a research on comparison between experimental and numerical (finite element method) studies of low-velocity impact on sandwich panels with honeycomb core. Two boundary conditions were considered, which were rigidly supported and four sided clamped. The model was simulated using ANSYS. It was found that the numerical results were reliable and approximate with experimental results with error range from 3% to 12%. And, the shear failure of the core was the first failure that took place in almost all the tests. Another research regarding the low-velocity impact response of composite sandwich plate was conducted by Foo *et al*. [7]. Two types of plate namely square and circular aluminum sandwich plates were investigated experimentally using energy-balanced method and finite element model using ABAQUS software. It was found that in the numerical modeling, the simulation runtime for circular plate was reduced to 25% compared to square plate. In terms of energy absorption, the energy absorbed by the plates was independent of the core density. Besides that, as the density of the core increases, the impact damaged areas in both core and facesheets were reduced. Continuous core crushing, delamination and fiber fracture will occur if more loading was applied. Also, the predicted load-time and load-deflection histories were found to be more accurate by implementing the combination of energy-balanced approach and impulse-momentum equation. Williamson and Lagace [8] experimentally studied the responses of honeycomb sandwich panels under impact loading. The experiment was performed using static indentation tests. Two boundary conditions were considered in this study; fully backed and two-sided clamped. The indenter shape was hemispherical-nose tups or cylinder. It was found that the top facesheet was damaged first before the core. The core was damaged after the penetration took place on the top facesheet. In addition, for the two-sided clamped composite sandwich panels, the bottom facesheet was not damaged before the failure of both top facesheet and core because of low strain after impact. Hoo Fatt and Park [9] studied composite sandwich panels, with symmetric orthotropic laminated facesheets and core that has a constant crushing resistance, subjected to low-velocity impact. They found that initial damage mode that would occur after impact was influenced by boundary conditions, type of impactor/indenter as well as geometric and material properties of both facesheets and core. Also, the predicted results from this study showed good compatibility with the experimental results from previous studies. Ju *et al*. [10] analyzed numerically the shear behaviors of different honeycomb configurations for two types of materials; mild-steel and polycarbonate. The single layer design and the angle with higher negative degrees of honeycomb displayed better results. By using finite element method, Abo Sabah and Kueh [11] carried out the analysis on low-velocity impact at the center of laminate composite plate with various lamination schemes. This paper only focuses on the delamination failure of the plate. It was found that an increase in the plies angles difference produce greater maximum displacement and delamination area. Hosseini and Khalili [4] studied the indentation and low-velocity impact responses of fully backed composite sandwich plates analytically, which involved nonlinear analysis. The indenter/impactor used was rigid flat-ended cylindrical. An improved contact law (contact force – indentation relation) was introduced in this study. A spring-mass-dashpot model was performed for the analysis of low-velocity impact of composite sandwich plates. It was observed that the results from this study were compatible with the experiment results from Williamson and Lagace [8]. Also, this study showed that the stacking sequence of the facesheet affects the static indentation and impact responses of the composite sandwich plate by only a little.

So far, not many researches consider indentation in the modeling of the composite sandwich plate. Although there was a study on indentation of composite sandwich plate, it did not consider the strain failure of the structure. Strain failure is related to the indentation in determining the failure of the structure in terms of strain. The occurrence of indentation on the composite sandwich plate does not necessary mean a consequent failure in strain. In this research, the main concerns include; the formulation for modeling the composite sandwich plate by means of finite element, investigation on strain failure, indentation and global displacement of composite sandwich plate and parametric studies on composite sandwich plate. The formulation has been limited to the core with a honeycomb configuration, loading at the center, low-velocity impact, flat-ended cylinder impactor and fixed supported plate.

2.0 MODEL DESCRIPTION

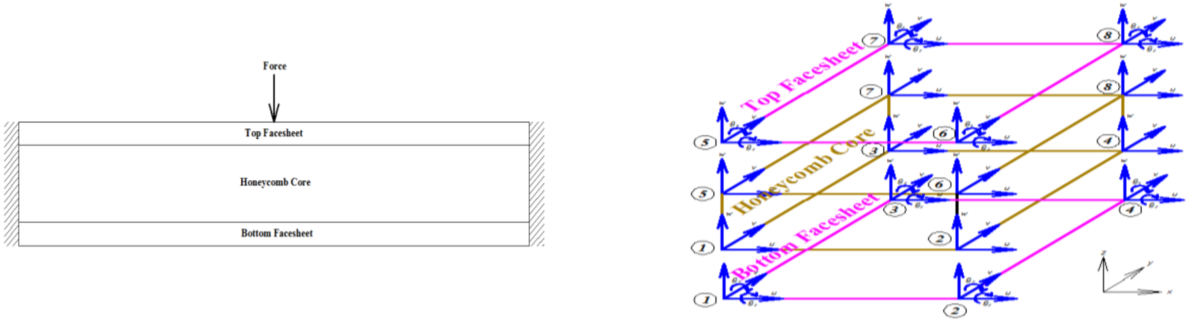
The model arrangement is in accordance with Williamson and Lagace [8] experiment, as shown in Figure 1. This model consists of two-ply composite skin with fiber orientations of 0° and 90° at the top and bottom, respectively. Type of core used in this study is honeycomb core. The properties of the facesheets, honeycomb core and impactor are shown in Table 1. The plate has a square cross-section of 102×102×26.1 mm with a fixed-end boundary condition along all edges.

2.1 Modeling Procedure

Figure 2 shows the general procedure of the finite element formulation and solution technique appointed for the composite sandwich plate under low-velocity impact. In detail, the model is described in the followings.

2.2 Formulation of Stiffness Matrix

The stiffness matrix of composite sandwich plate is formed by combining the stiffness matrix of the top facesheet with the upper half of honeycomb core and the bottom facesheet with the lower half of honeycomb core.



(a) Sideview of the composite sandwich plate

(b) Global assembly of composite sanwich plate sub-element

Figure 1 Fixed-end composite sandwich plate model under an impact load

Table 1 The properties of the facesheets, honeycomb core and impactor [8]

Properties	Details
The Properties of the Facesheets:	
Material	Hercules AW193-PW prepreg consisting of AS4 fibers in a 3501-6 matrix (carbon/epoxy)
Fiber Orientation	Cross-ply laminates – [0/90]
Ply Thickness, t_f	0.175 mm
Density	1.6173×10^{-6} kg/mm^3
Longitudinal Extensional Modulus, E_1	1.42×10^5 N/mm^2
Transverse Extensional Modulus, E_2	9.8×10^3 N/mm^2
Poisson ratio, v_{12}	0.3
In-plane shear modulus, G_{12}	7.1×10^3 N/mm^2
Static tensile failure strain	0.0112
The Properties of the Honeycomb Core:	
Material	HRH 10 1/8-3.0 Nomex honeycomb (Ciba-Geigy)
Geometry	Honeycomb (Hexagonal)
Thickness	25.4 mm
Density	$4.8\text{x}10^{-8}$ kg/mm^3
Young's modulus, E_c	3500 N/mm^2
Cell diameter	3.2 mm
Wall thickness	0.063 mm
Crushing resistance	1.389 N/mm^2
The Properties of the Impactor:	
Material	Case-hardened steel
Shape of Indenter	flat-ended cylinder
Mass	1.612 kg
Diameter	25.4 mm
Initial Velocity	1.2 m/s
Impact duration	0.06

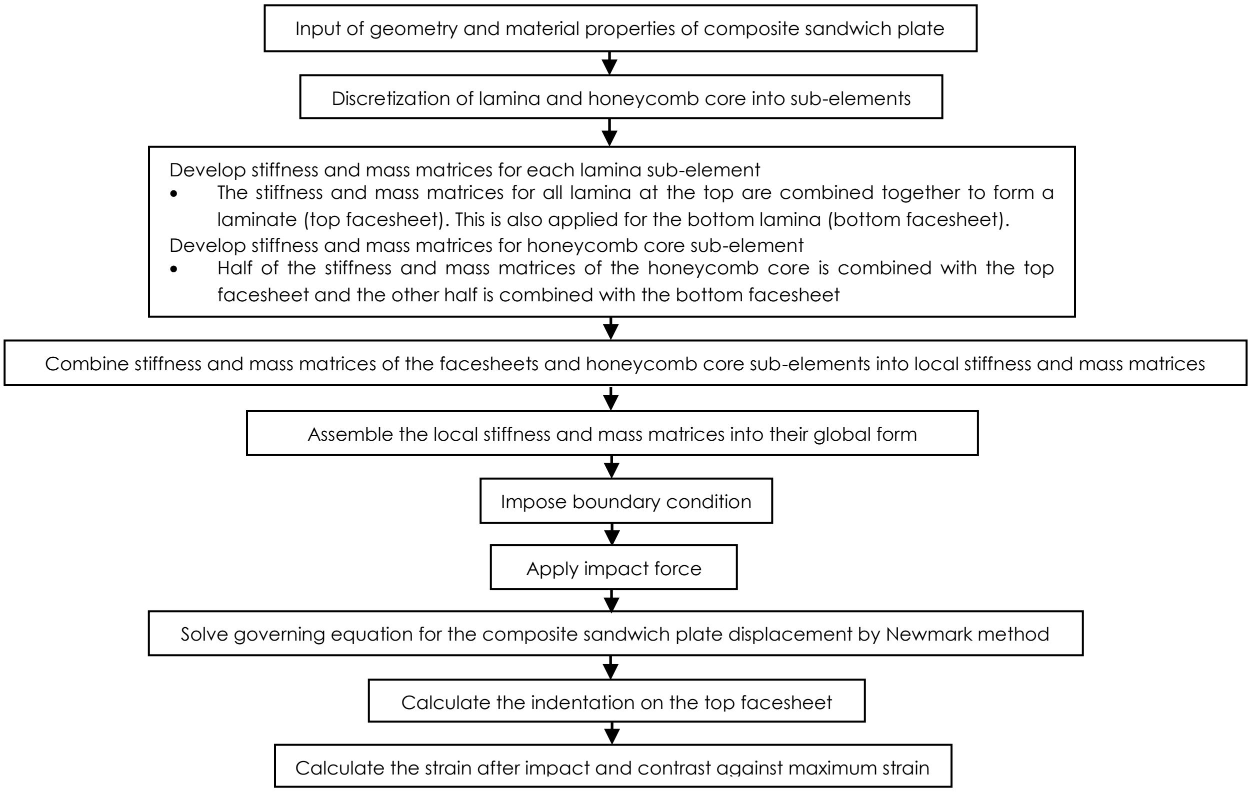


Figure 2 Finite element analysis procedure for composite sandwich plate with honeycomb core under low-velocity impact

2.2.1 *Stiffness Expression for Facesheets*

The stiffness matrix for the facesheets, K_f, is formulated using the ABD matrix and integrated based on an isoparametric formulation.

$$K_f = \iint [B_i^T (A)_{ABD} B_i + B_i^T (B)_{ABD} B_o + B_o^T (B)_{ABD} B_i + B_o^T (D)_{ABD} B_o] |J|\, d\zeta\, d\eta \qquad (1)$$

where B_i is the in-plane strain-displacement matrix, B_o is the out-of-plane strain-displacement matrix, $(A)_{ABD}$ is the extensional stiffness, $(B)_{ABD}$ is the coupling stiffness, $(D)_{ABD}$ is the bending stiffness and J is the Jacobian matrix.

2.2.2 *Stiffness Expression for Honeycomb Core*

The stiffness matrix for the honeycomb core, K_{core}, is

$$K_{core} = \frac{1}{h} \iint B_{core}^T D_{core} B_{core} |J|\, d\zeta\, d\eta \qquad (2)$$

$$D_{core} = \begin{bmatrix} G_{xz} & 0 & 0 \\ 0 & G_{yz} & 0 \\ 0 & 0 & E_z \end{bmatrix} \qquad (3)$$

where h is the thickness of honeycomb core, B_{core} is the element strain-displacement matrix, D_{core} is the constitutive matrix of honeycomb core and J is the Jacobian matrix.

2.2.3 *Mass Matrix*

The mass matrix of composite sandwich plate is formed by combining the mass matrix of the top facesheet with the upper half of honeycomb core and the bottom facesheet with the lower half of honeycomb core. The consistent mass method is used.

$$M_i = \rho_i t_i \iint N_i^T N_i |J|\, d\zeta\, d\eta \;;\; i = f \text{ for facesheet and } i = c \text{ for honeycomb core} \qquad (4)$$

where ρ is the density of material, t is the material thickness, N_i is the element shape function and J is the Jacobian matrix.

2.2.4 *Impact Force*

The approximate impact force formula, $F(t)$, is described as

$$F(t) = \frac{m v_o \pi}{t_o} \sin \frac{\pi t}{t_o} \qquad (5)$$

where m is the impactor mass, v_o is the initial velocity, t is the time taken and t_o is the impact duration.

2.2.5 *Contact Force–Indentation Relation*

To describe contact force – indentation relation, we have [4]

$$P = \frac{8\sqrt{E_1 q}\,\delta^{3/2}}{3} + \pi q R^2 + \frac{1}{15}\delta(16N_{xx} + 16N_{yy} + 16N_{xy}) \quad (6)$$

$$E_1 = \frac{8}{45}A_{11} + \frac{8}{45}A_{22} + \frac{32}{49}A_{66} + \frac{16}{49}A_{12} + \frac{2}{3}A_{16} + \frac{2}{3}A_{26} \quad (7)$$

where *P* is the contact force, *q* is the crushing resistance of honeycomb core, *δ* is the indentation, *R* is the radius of the indenter, *N* is the initial in-plane forces acting on the edge of the composite sandwich plate and *A* is the extensional stiffness of ABD matrix of the facesheet.

2.2.6 Strain Failure

Strain failure analysis is only carried out for the top facesheet. The strain after impact is compared with the maximum strain. If the strain after impact is more than the maximum strain, the lamina is considered damaged and vice versa. The formulation of the strain after impact, ε, is

$$\varepsilon = \varepsilon_o + z\kappa \quad (8)$$

Where ε_o is the mid-plane strain of laminate, *z* is the through thickness direction of laminate and *κ* is the mid-plane curvature of laminate.

3.0 RESULTS AND DISCUSSION

3.1 Verification

Figure 3 shows the verification of contact force – indentation relation. From the graph, the indentation from the analytical prediction by Hosseini and Khalili [4] is similar to the indentation computed by the present model although it is slightly higher than that by Williamson and Lagace [8]. Therefore, it is evident that a good agreement has been found, exhibiting applicability of the present model.

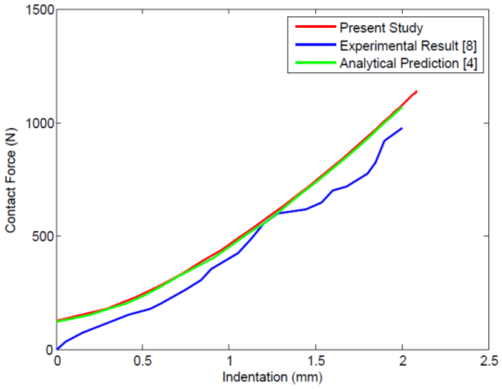


Figure 3 Verification of contact force – indentation relation

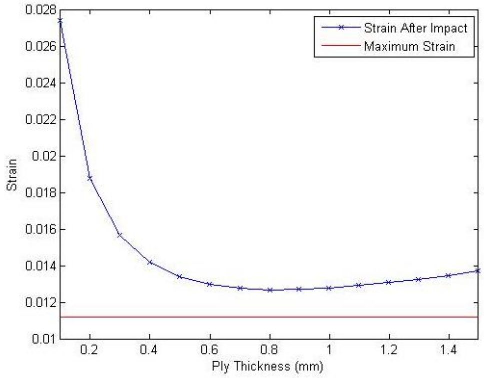
3.2 Strain Failure

For currently considered case, Table 2 shows the strain failure of lamina of the top facesheet. Both laminas (0° and 90°) exceed the maximum strain of 0.0112. Therefore, both laminas cannot withstand the impact and fail.

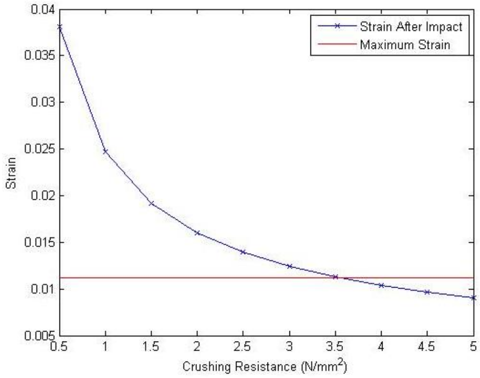
Table 2 Strain failure of lamina of the top facesheet

Lamina	Fiber Orientation	Strain	Maximum Strain Exceeded?
1	0°	0.020068	Yes
2	90°	0.015663	Yes

Several parameters are investigated in order to improve the lamina from severe failure due to the impact, including the number of ply, ply thickness of top facesheet and crushing strength of core. Strain after impact for first ply (0°) is plotted as shown in Figure 4(a). Figure 4(b) shows the strain after impact and maximum strain against crushing resistance of core for first ply (0°).



(a) Strain after impact against ply thickness for first ply (0°)



(b) Strain after impact against crushing resistance of core for first ply (0°)

Figure 4 Ply thickness and crushing resistance effects on strain failure analysis

It is obvious that ply thickness improves the experienced strain after impact although all thicknesses produce strain higher than that of maximum. The most effective parameter that can improve the strain failure of sandwich composite plate is the crushing strength of the core. The minimum crushing strength that can be used to avoid strain failure is approximately equal to 3.557 N/mm^2 limited to the model configuration studied in this study.

3.3 Relationship between Thickness and Young's Modulus of Core

Figure 5 shows the relationship of d/L against $(E_c/A_{11})h$, where d is the displacement, *L* is the length of plate, E_c is the Young's modulus of the core, A_{11} is the extensional stiffness and *h* is the core thickness. It can be seen that each curve is overlapping each other. The higher the thickness and Young's modulus of core, the lower the displacement of composite sandwich plate is and vice versa.

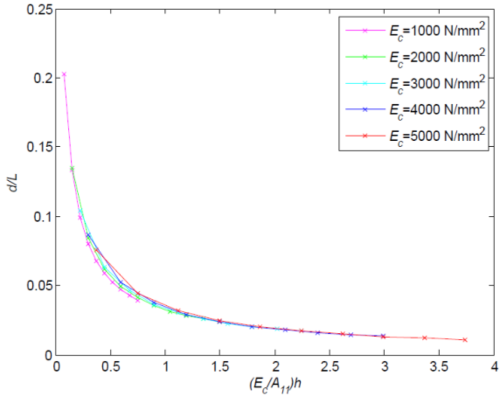


Figure 5 d/L against $(E_c/A_{11})h$

3.4 Relationship between Crushing Resistance and Thickness of Core

Figure 6 shows the non-dimensional graph of δ/L against $(q/A_{11})h$, where δ is the indentation and q is the crushing resistance.

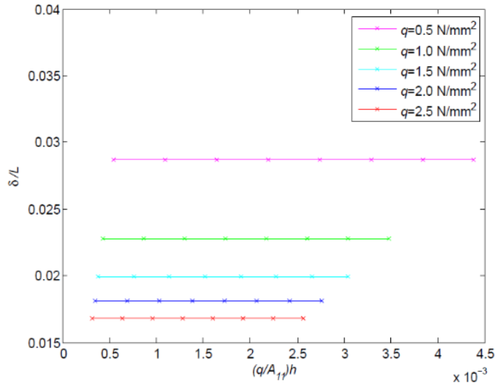


Figure 6 δ/L against $(q/A_{11})h$

Based on the graph, each crushing resistance produces an unperturbed curve. This means that the thickness of the core is not affecting the indentation on the composite sandwich plate. Only the crushing resistance of core affects the indentation performance. It can be clearly seen that as the crushing resistance increases, the indentation will decrease and vice versa.

3.5 Relationship between Crushing Resistance and Ply Thickness

Figure 7 shows the relationship of δ/L against $(q/A_{11})t_f$, where t_f is the ply thickness. By increasing the ply thickness of the top facesheet, the extensional stiffness matrix, A_{11}, will also increase, which results in smaller $(q/A_{11})t_f$ and this indirectly leads to a smaller indentation. For currently considered case, the relationship of indentation with respect to core crushing resistance, top facesheet thickness, and top facesheet extensional modulus is found to be

$$\delta = \frac{1497.5q}{A_{11}} t_f L \qquad (9)$$

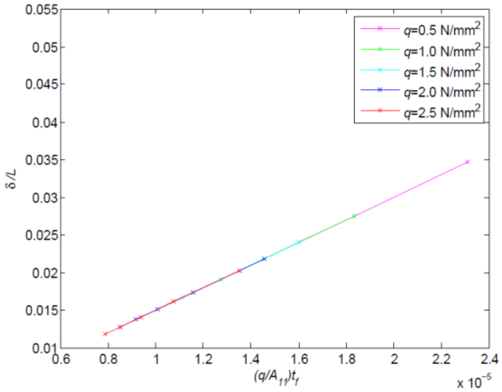


Figure 7 δ/L against $(q/A_{11})t_f$

4.0 CONCLUSION

From the present study, the followings can be concluded:

(a) The formulation for composite honeycomb core sandwich plate under low-velocity impact with the indentation and strain failure descriptions are developed.

(b) The validity of the present formulation is verified with existing modeled and experimental results.

(c) The indentation on the top facesheet can be reduced by increasing the number of ply, ply thickness as well as crushing resistance of core.

(d) The global displacement of composite sandwich plate can be reduced by using higher core thickness and Young's modulus of core.

(e) The most effective parameter that can improve the strain failure of the facesheets of the sandwich composite plate is the crushing resistance of the core.

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