ABSORPTION ENERGY OF LAYERED STRUCTURES DUE TO IMPACT LOADING

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To my beloved parents

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ABSTRACT

In this study, the finite element formulation for the investigation of the effects of a localized interfacial delamination on the energy absorption of the [90˚/0˚] laminated composite plate under impact loading is conducted. The stiffness of the laminate is determined by assembling the stiffnesses of sub-elements contributed by top and bottom laminae as well as the interface under impact loading. An introduction of an interface layer with stress- and strain- influenced material description is proposed to model a more realistic interfacial delamination. Also, the kinematically consistent mass matrix and mass proportional damping are formulated to complete the transient vibration governing expression. To simulate the interfacial degeneration of the laminate, it is defined in a localized manner in accordance with the maximum stress and strain of material under study induced by impact loading. The effects of localized interface delamination on the laminated composite plates when subjected to low velocity impact loading for various energies are investigated. Generally, the central displacement and degenerated area of interface increases as the impact energy increased. In addition, the absorption energy by the interface is rises due to higher impact energy. More realistic damaged models offer greater absorption energy compared to those undamaged.

ABSTRAK

Dalam kajian ini, perumusan unsur terhingga untuk menyiasat kesan daripada pemishahan antratamuka setempat pada penyerapan tenaga plat komposit berlapis [90˚/0˚] di bawah beban hentaman dijalankan. Kekukuhan laminat ditentukan oleh pengumpulan kekukuhan sub-elemen yang disumbangkan oleh lamina bahagian atas dan bawah serta antaramuka. Satu pengenalan lapisan antara muka dengan keterangan bahan yang dipengaruhi ketegasan dan keterikan telah dicadangkan untuk memodalkan pemisahan antaramuka yang lebih realistik. Sementara itu, matriks jisim konsisten secara kinematik dan redaman berkadar jisim telah dirumus untuk melengkapkan expressi pengawal getaran berjangkamasa. Untuk mensimulasikan degenerasi antara muka lamina, ia ditakrifkan secara setempat mengikut tepasan dan terikan maksimum bahan yang dikaji disebabkan oleh pembebanan hentaman. Kesan kemerosotan setempat antara muka pada plat komposit berlapis apabila dikenakan halaju rendah untuk pelbagai tenaga telah disiasat. Secara amnya, anjakan pusat dan kawasan merosot antaramuka bertambah apabila tenaga hentaman yang meningkat. Di samping itu, tenaga penyerapan oleh antaramuka mengikat kerana kenaikan hentaman. Modal yang mengandungi sifat kerosakan yang lebih realistik menghasilkan tenaga penyerapan yang lebih tinggi berbanding model tanpa kemorostan.

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$\{M\}$	-	Global mass matrix
$\{C\}$	-	Damping matrix
$\{\ddot{q}\}$	-	Nodal acceleration
$\{\dot{q}\}$	-	Nodal velocity
$\{q\}$	-	Nodal displacement
V_f, V_m	-	Volume fraction of fiber and matrix respectively
E_f, E_m	-	Young Modulus of fiber and matrix respectively
G_{12f}, G_m	-	Shear modulus of fiber and matrix respectively
v_{12f}, v_m	-	Poisson's ratio of fiber and matrix respectively
E_1	-	Longitudinal Young's modulus
E_2	-	Transverse Young's modulus
G_{12}	-	In-plane shear modulus
υ_{12}	-	Poisson's ratio
ξ	-	Measure of fiber reinforcement coefficient that depends on the fiber geometry, packing geometry, and loading conditions. The value of ξ is taken as 2 for E_2 calculation while 1 for G_{12} calculation.
Q_{ij}	-	Lamina stiffness matrix
$\overline{Q}_{ij}$	-	Transformed stiffness matrix
N	-	In-plane force
M	-	In-plane moment
ε^0	-	Mid-plane strain
κ	-	Mid-plane curvature
A_{ij}, B_{ij}, D_{ij}	-	Laminate extensional stiffness, laminate-coupling stiffness, and laminate-bending stiffness respectively

u, v, w	-	Displacement in x, y, z direction respectively
$Ø_y, Ø_x$	-	Rotation about the x, y direction respectively
N_i, N_o	-	Shape function for in-plane and out-of-plane degree of freedom respectively
$[B]$	-	Strain-displacement matrix
$[N]$	-	Shape function
$[B_i]$	-	In-plane element strain-displacement matrix
$[B_o]$	-	Out-of-plane element strain-displacement matrix
ζ_i, η_i	-	Coordinates of node
ζ, η	-	Value of Gauss point
a, b	-	Length and width of element respectively
$[K]$	-	Stiffness matrix
$\{F\}$	-	Nodal load
$\{d\}$	-	Nodal displacement of the laminate
d_{lower}	-	Interpolated displacement of node at lower surface of the zero-thickness element
d_{upper}	-	Interpolated displacement of node at upper surface of the zero-thickness element
$\hat{d}_{lw}$	-	Nodal displacement of node at lower surface of the zero-thickness element
$\hat{d}_{up}$	-	Nodal displacement of node at upper surface of the zero-thickness element
$[B_{\text{int}}]$	-	Interface element strain matrix
σ	-	Stress
ε	-	Strain
D	-	Constitutive matrix
h	-	Thickness of interface element
J	-	Jacobian matrix
w_i, w_j	-	Weight of i^{th} and j^{th} Gauss point
$f(\zeta_i, \eta_j)$	-	Function of i^{th} and j^{th} Gauss point

$\overline{K}^{L}$	-	Stiffness matrix for linear part
$\overline{K}_{G}$	-	Geometric stiffness matrix
λ	-	Buckling load parameter
$\overline{d}$	-	Nodal displacement
$\overline{p}$	-	Applied force
t	-	Element thickness
$\overline{P}_{x}$, $\overline{P}_{y}$	-	Membrane applied load per unit area in *x* and *y*-direction, respectively, prior to buckling
$\overline{P}_{xy}$	-	Applied shear load per unit area prior to buckling
$w{,}x$, $w{,}y$	-	Lateral displacement in partial differentiation with respect to *x* and *y* respectively
$\{v\}$	-	Element nodal displacement
m_{i}	-	In-plane mass matrix of the element
m_{o}	-	Out-of-plane mass matrix of the element
m_{area}	-	Mass of the plate per unit area
α	-	Mass proportional damping coefficient
β	-	Stiffness proportional damping coefficient
$[K_{ef}]$	-	Effective stiffness
$[F_{ef}]$	-	Force stiffness
V_{o}	-	Initial velocity of impactor
m	-	Mass of compactor

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

In recent years, composite materials has become one of the main application materials in advanced engineering, primarily as components in civil engineering structures, aerospace, automotive and other structural applications. It has high mechanical properties with low weight composite material. Usually, they are fabricated as laminated structures where two or more laminas are bonded by a layer of adhesive material. The composite laminated materials are able to achieve required strength and stiffness properties to specific design conditions through proper arrangement of stacking sequence, fiber orientation, thickness and material properties of each layer. Figure 1.1 indicates an example of a laminated composite, demonstrating two face layers with an interface layer. The face layers are laminar plates and viscoelastic material as the interface layer.

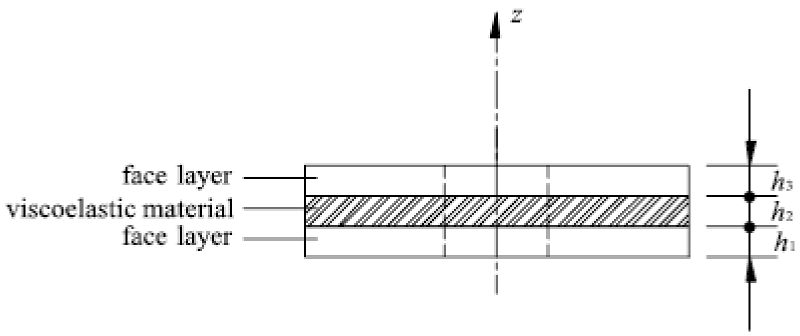


Figure 1.1 Two layers laminated composite with an interface layer (Wang and Chen, 2002).

The dynamic response such as natural frequency, modal damping and loss factor depend on the material density, elastic constants, damping properties, geometry and layers orientations. Therefore, damping has become one of the important parameters related to the study of dynamic behavior of composite laminated structures. Damping usually occurs as a mixture of two mechanisms in a composite laminated. One of the mechanisms is damping between the fiber and adhesive layer within the laminated plies and the other mechanism is damping between the plies or between the laminated.

The equation of motion for damped system in free vibration environment can be written as:

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = 0 \qquad (1.1)$$

where
$[M]$ is the global mass matrix,
$\{\ddot{q}\}$ is the nodal accelerations,
$[C]$ is the global proportional matrix,
$\{\dot{q}\}$ is the nodal velocity,
$\{K\}$ is the global stiffness matrix,
$\{q\}$ is the nodal displacement.

The damping behavior of the laminated composite plate can be determined by using the finite element theory. In general, damping matrix, $[C]$, which is introduced by the finite element theory can be assembled from damping properties of material. In order to conduct a modal analysis of damped systems, it is common to presume the proportional damping, which is a special type of viscous damping. The proportional damping model defines the damping matrix as a linear combination of the mass and stiffness matrices:

$$[C] = \alpha[M] + \beta[K] \qquad (1.2)$$

where α and β are are computed the required levels of proportional damping at two different frequencies.

Therefore, the equation makes damping frequency-dependent. Four types of physical damping can be modeled in finite element techniques as shown below:

i) Undamped case (α = 0; β = 0)
ii) Stiffness-proportional damping (α = 0; β > 0)
iii) Mass-proportional damping (α > 0; β = 0)
iv) Rayleigh damping (α > 0; β > 0)

Although composite laminated has almost unlimited potential in satisfying the strength requirement, they may exhibit several peculiar modes of failure such as matrix crazing, delamination, fiber failure and interfacial bond failure due to debonding. Figures 1.2 shows interfaces and bonding layers of laminated composite.

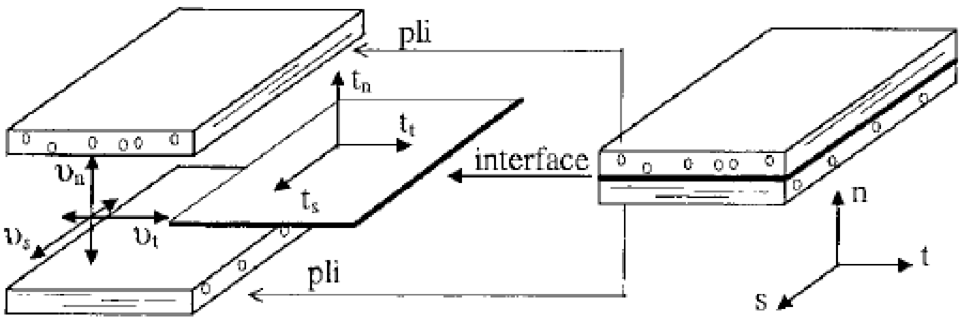


Figure 1.2 Interfaces and bonding layers of laminated composited, (Bui, Marechal and Nguyen-Dang, 2000b).

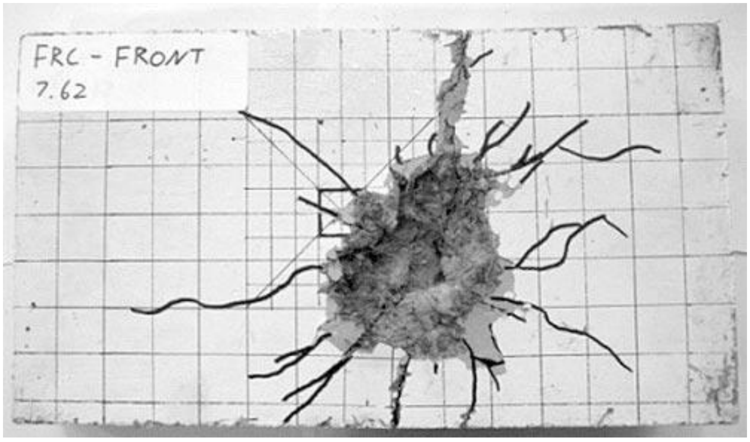
In reality, it is impossible to have a perfect interfacial bond especially during manufacturing process or the actual service life of composite laminates. One of the most common failures, the delamination, is an interlayer separation damage mode, which possibly occurs in the interface of a laminated composite. Therefore, a model of composite laminated with imperfect interfaces due to impact load should be adopted since significant contribution of imperfect laminates on the mechanical responses has recently been recognized (Bui, Marechal and Nguyen-Dang , 2000).

In addition, the demand of lightweight, high strength and high energy absorption of material has increased in construction industry. In order to improve performance of composite material against strong wind and ground motion, interface layers have been generally used. Interface layers have advantages on isolating vibration, absorbing shock and reducing noise if proper material is used. Generally, the interface layer is used to resist the vibration and shock load in order to absorb the energy and emit energy absorbed as heat so as to protect the material from damage. Interface layer will absorb kinetic mechanical energy when compressed or deflected at a relatively low stress over an extended distance, and not rebounding. Thus, it is essential to capture the effects of a proper mechanical description of interfacial method in resisting impact load in terms of energy absorption capability.

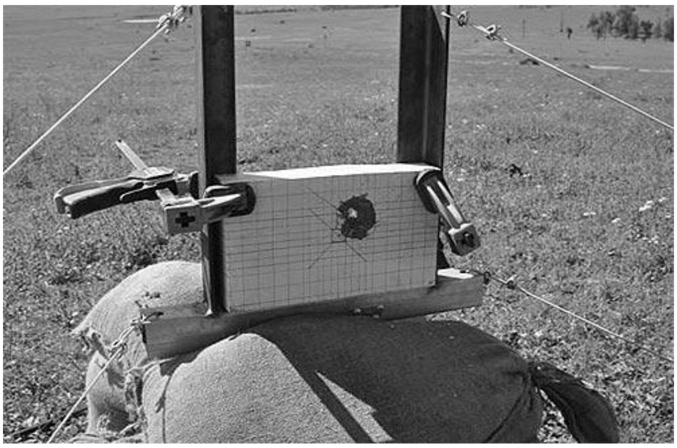
The composite laminated are known to be susceptible to damage resulting from impact load of foreign objects. The impact load causes the laminated composite to resist a high energy in a short time period. Impact on composite laminated is a dynamic problem, which leads to a local damage phenomena. It is the most significant damage in laminated composite subjected to impact force due to the invisible damage to the back face. Hence, the general problem of impact is extremely complex.

Laminated composite is prone to damage by impact loads during manufacturing, transportation or service life. The effect on the response of mechanical properties of laminated composite under impact load has become one of the issues in many advanced engineering structures. Figure 1.3 shows examples of damage of composite material caused by an impact load.

(a)



(b)



(c)

Figure 1.3 Examples of damage on composite material caused by impact load: (a) Damaged steel bar-reinforced concrete panel (b) Damaged steel-fiber reinforced FRC panel (c) Damaged hybrid-ECC panel, (Zhang, 2012).

In response to this issues, Rahme et.al. (2012) suggested adding a mechanical protection on composite structures. An experiment study of low energy impacts on composite plates covered protective layer was conducted. Figure 1.4 shows that the damage can be reduced by using a protection layer on the surface of plate. Two configurations of protective layers have been tested. Configuration 1 is designed for 50 J energy impacts as shown in Figures 1.5. It is composed of a 1.4 mm thick $0^{o}/90^{o}$ Kevlar woven fabric skin and of a polymer hollow spheres core made by ATECA Company. Sphere diameter is between 5.4 and 6 mm, and spheres are glued together as well as with the skin.

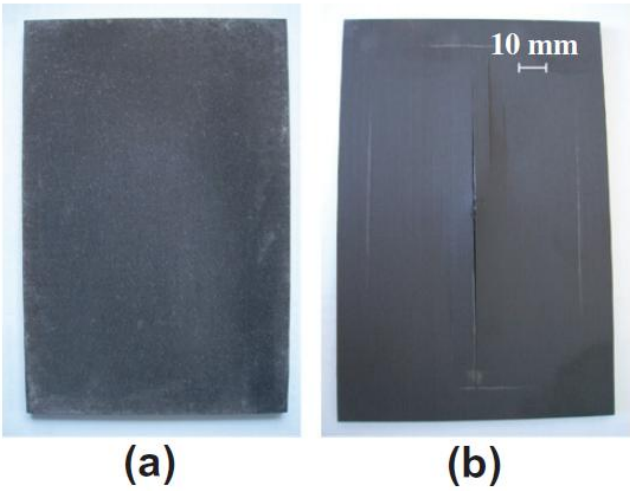


Figure 1.4 Composite plate impacted at 50J: (a) with protective layer (b) without protective layer (Rahme et.al., 2012).

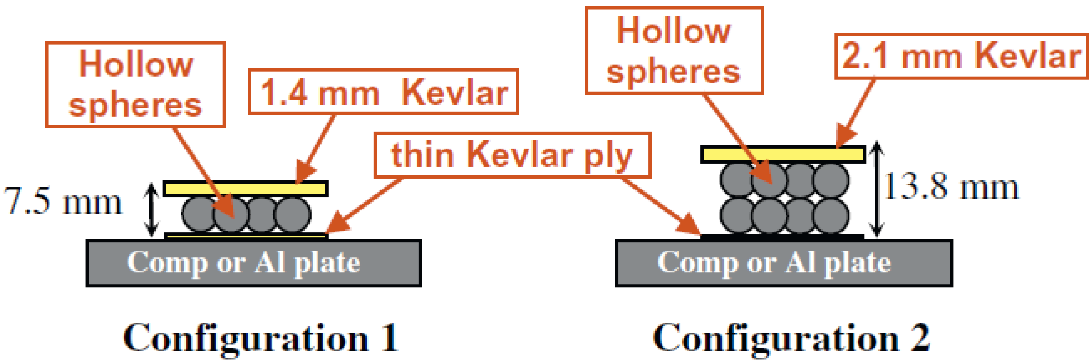


Figure 1.5 Two configurations with protective layers (Rahme et.al., 2012).

1.2 Problem Statement

Generally, the dynamic resonance technique is used to evaluate the modulus and damping behavior of a variety of materials such as composite laminated plate. Damping is an energy dissipation mechanism in reducing the resonant vibration of material. Thus, the total energy dissipated at the viscoelastic interface due to impact loading has become an interest in order to determine the behavior of composite laminated plate. The higher energy absorbed at interface, the better resistance to chatter phenomenon such as earthquake, strong wind and shock load. According to Shariyat and Hosseini (2014), the viscoelastic layer has high energy absorption ability, which can provide better control on the structure vibration and noise.

Due to high labor and cost demands of experimental studies, the predictions of changes in structural dynamic properties can be investigated by using the finite element method. With the modeling of degeneration of localized interfacial in composite laminated plate in accordance with experienced stress and strain changes induced by impact load, the accuracy to predict the failure will be improved and more realistic. An accurate modeling expression for energy absorption due to low-velocity impact loading is essential in describing better the material properties of laminated composite structures.

Most of the interfacial model adopted linear and constant material properties. Therefore, they are incapable of modeling accurately the energy absorption effect contributed by the interfacial material. Hence, better description of model in analysis should be conducted to develop knowledge that can be used to improve the energy absorption of the interface based on stress- and strain-induced behaviour.

1.3 Objectives

This study is concerned with the energy absorption of layered structure due to impact loading. The main objectives of this study are:

a) To formulate the finite element model for a two-layer composite plate with a defined interface element incorporating more realistic stress- and strain induced material description in presence of impact load.
b) To develop the MATLAB code for the aforementioned finite element model.
c) To determine the damage initiation and progress of interface due to impact loading with stress- and strain- influenced localized interfacial degeneration.
d) To investigate the effects of energy absorption due to impact loading with stress- and strain- influenced localized interfacial degeneration.

1.4 Scope of the Study

The main structure studied is a rectangular laminate plate. The laminated composite plate is considered to be thin and flat according to thin plate theory. The shear deformation is neglected. The laminated composite plate is constructed from two layers of lamina with equal thicknesses and an interfacial layer in between. Each lamina is formed by unidirectional fibers, the E-glass, and the matrix material, epoxy 3501-6, with a volume fraction of fiber 0.4. A cross-ply laminate plate configuration is considered in this study. The top lamina is of 90 degrees fiber direction and the bottom lamina is of 0 degree fiber direction. The initial velocity of the impactor is 1.0-1.5 m/s having a 0.2-0.5 kg weight and 0.002 s impact duration. This time span is chosen such that an appreciable deformation can be observed in simulation. Only impacts of low velocity are considered in this study. The boundary condition of the plate is fully clamped at all edges.

The lamina is modeled and discretized by using a rectangular plate finite element with 4 nodes. In this study, the laminated composite plate is considered as a transversely isotropic solid material. There are five degrees of freedom for each of the nodes, which are displacement in *x*-direction (*u*), displacement in *y*-direction (*v*), displacement in *z*-displacement (*w*), rotation about *y*-direction ($\o_x$) and rotation about *x*-direction ($\o_y$).

Besides that, the interfacial layer is considered as an orthotropic material with null normal stresses in *x*-direction and *y*-direction as well as the in-plane shear stress on *x*-*y* plane ($\sigma_x=\sigma_y=\tau_{xy}=0$). It is modeled using a quadrilateral solid element with 8 nodes. However, there are only three degrees of freedom for each node, which are the displacement in *x*-direction (*u*), displacement in *y*-direction (*v*), and displacement in *z*-displacement (*w*). The stiffness matrix of the lamina and interfacial element is computed using a 2×2 Gauss quadrature rule.

This model is applied to describe the energy absorption at interface due to low velocity impact. The load is applied at the center of the plate without taking into consideration the impactor shape. To simulate the interfacial degeneration of the laminate, the degenerated areas are defined in a localized manner in accordance with stress and strain induced by impact loading.

1.5 Significance of the Study

Composite laminated material has been widely used in construction industry in the past several decades. The composite laminated material such as plate element is very common in structures. This has made the study of the dynamic behavior of composite laminated plate important. In most cases, the bonding layer of composite laminated plate is assumed to be perfect. However, it is impossible to have a perfect bonding during the manufacture process. Therefore, the debonding area may exist between the layers of composite laminated plate.

The behavior of composite laminated plate is highly depended on the dynamic properties such as natural frequency and loss factor. As the debonding or delamination occur on the interfacial layer of laminated plate, the dynamic properties will change with respect to the area of degeneration. Hence, improvement in prediction can be accessed from the comparison of perfect bonding and imperfect bonding cases. On the other hand, a mass proportional damping model is considered.

With the wide application of laminated composite plate, the ability of strength and energy absorption of plate is desired. It is practically dangerous in applications when the laminated composite plate is attacked by external load especially impact load. In order to enhance the energy absorption, interface layer of composite laminated plate is encounter to make the modeling more realistic.

In many structural design problems, the requirement is to provide proof that the structure remains considerably safe even though damaged. Therefore, the effect of energy absorption of the composite laminated plate due to impact load is required in structural behavior investigation.

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