FINITE ELEMENT MODELING OF LAMINATED COMPOSITE PLATES WITH LOCALLY DELAMINATED INTERFACE SUBJECTED TO IMPACT LOADING

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This project report is dedicated to my beloved parents.

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ABSTRACT

This project report presents the finite element formulation for the investigation of the effects of interface imperfection on the impact behavior of a laminated composite plate. The interface condition between the laminas plays a very important role in the determination of the behavior of the composite laminates. If the bonding is imperfect, it has high possibility to delaminate progressively. Most of the previous studies on laminated composites were carried out adopting the assumption that the laminas are perfectly bonded. However, the existence of a perfect interfacial bond in a real laminated composite seems to be impossible. Therefore, this study aims to investigate the effect of localized interface imperfection on the behavior of a laminated composite plate when subjected to low velocity impact loading for various fiber orientations. A thin, flat, rectangular laminated plate with two layers of E-glass/Epoxy transversely isotropic lamina and an orthotropic interface layer between them are considered in this study. The interface is modeled as a layer of zero thickness and zero mass, and the imperfection factor is applied locally to the interface. By using MATLAB, the stiffness matrix, mass matrix, and the impact force vector are formulated and programmed in order to obtain the deformation of the plate. The results show that as the separation of fiber orientation between the two laminas increases, both central deflection and energy absorption increase. The increase of delamination area leads to plate's damage due to the increase in the absorbed energy, resulting in higher deformation.

ABSTRAK

Laporan projek ini membentangkan rumusan unsur terhingga bagi menyiasat kesan ketidaksempurnaan antaramuka pada tingkah laku impak plat komposit berlapis. Keadaan antaramuka lamina memainkan peranan yang amat penting dalam menentukan tingkah laku komposit berlapis. Jika ikatan tidak sempurna, ia mempunyai kemungkinan yang tinggi untuk berpisah secara progresif. Kebanyakan kajian terdahulu mengenai komposit berlapis telah dijalankan dengan menggunakan andaian bahawa lamina adalah terikat dengan sempurna. Walaubagaimanapun, kewujudan ikatan antaramuka yang sempurna dalam komposit berlapis sebenar adalah mustahil. Oleh itu, kajian ini bertujuan untuk mengkaji kesan ketidaksempurnaan setempat antaramuka pada kelakuan plat komposit berlapis apabila dikenakan beban impak halaju rendah untuk pelbagai orientasi serat. Plat berlapis segiempat nipis dan rata dengan dua lapisan isotropi melintang E-kaca/epoksi dan lapisan antaramuka ortotropik telah dipertimbangkan dalam kajian ini. Antaramuka telah dimodelkan sebagai lapisan ketebalan sifar dan berjisim sifar, dan faktor ketidaksempurnaan telah dikenakan secara setempat kepada antaramuka. Dengan menggunakan MATLAB, matriks kekukuhan, matriks jisim, dan vektor daya impak telah dirumus dan diprogramkan untuk mendapatkan ubah bentuk plat. Keputusan menunjukkan bahawa apabila pemisahan orientasi gentian antara kedua-dua lamina meningkat, kedua-dua pesongan pusat dan penyerapan tenaga juga meningkat. Peningkatan kawasan pemisahan membawa kepada kerosakan plat yang disebabkan oleh peningkatan dalam tenaga yang diserap, dengan akibat ubah bentuk yang lebih tinggi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

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 of the composite 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
$Ø_x$, $Ø_y$	-	Rotation about the x, y direction respectively
N_i, N_o	-	Shape function for in-plane and out-of-plane degree of freedom respectively
$[B]$	-	Element strain matrix
$[K]$	-	Element stiffness matrix
F	-	Force
q	-	Transversely distributed load
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
N	-	Lagrange shape function for 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
σ	-	Stress
ε	-	Strain
D	-	Constitutive matrix
h	-	Thickness of interface element
J	-	Jacobian matrix

ξ , η	-	Coordinate sysyem in Gauss quadrature rule
w_i , w_j	-	Weight of i^{th} and j^{th} Gauss point
$f(\xi_i, \eta_j)$	-	Function of i^{th} and j^{th} Gauss point

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Composite materials were introduced to several fields such as civil engineering, aerospace engineering and transportation industry a few decades ago. Composite materials are generally formed by combining two or more different materials with different physical and chemical properties in a microscopic scale. The combination of these materials produces a superior material that has all the properties of the combined materials. Thus, a composite material can provide an easy approach to design the right combination of fiber reinforcement and matrix material which meets the desired specifications.

As a matter of fact, there are two types of fiber reinforced composite materials as shown in Figure 1.1. The first type (Figure 1.1 (a)) is known as short fiber-reinforced composite. This type is normally used in compression and sheet moulding operations. The second type is referred to as continuous fiber-reinforced composite and it is shown in Figure 1.1 (b). It is formed of a layered or laminated structure. The applications of these fiber reinforced composites are usually used in the form of plates and shells. Composite plates are always organized in a flat laminate structure. Each layer of lamina contains an arrangement of unidirectional fibers embedded within a thin layer of polymer matrix material. Since a single layer of lamina has a very poor response to transverse tensile stress, each layer of lamina is stacked together with another layer in order to eliminate the weakness in the transverse direction. The fibers' function is primarily to carry the load whereas the matrix binds and protects fibers from any external damage. On the other hand, shells are curved composite materials. They have higher structural stiffness compared to plates in carrying loads and moments due to their curvature (Smith and Yeomans, 1995)

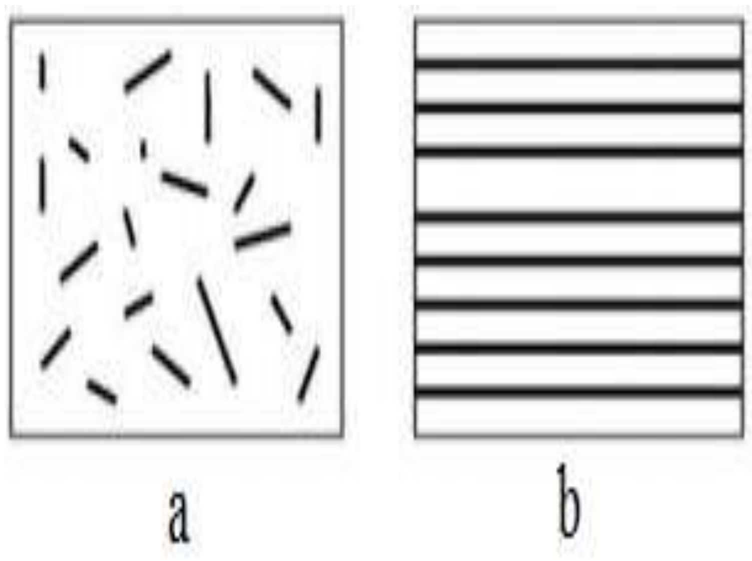

Figure 1.1 Types of fiber-reinforced composite material

During the manufacturing process of a laminate, a layer of adhesive (resin) is applied between the adjacent laminas to bond them together into one plate. After the application of the adhesive, the heat and pressure are introduced to the plate to make the adhesive bond the adjacent layers together in a process known as the lamination press process and the adhesive layer is called as the interface. Normally, the interface between the laminate is expected to be perfectly bonded. However, the existence of a perfect interfacial bond in a real laminated composite seems to be impossible. Therefore, the interface adhesion is usually imperfect. This imperfection is structurally harmful and contributes to the failure of the laminate when it is subjected to impact loading. The defects greatly influence the performance and mechanical properties of the laminate plate. The imperfection in the interface may be due to incorrect amounts of adhesive or incorrect equipment setting during manufacturing.

Figure 1.2 shows the typical sketch of the interface (bonding) layer in a composite laminate.

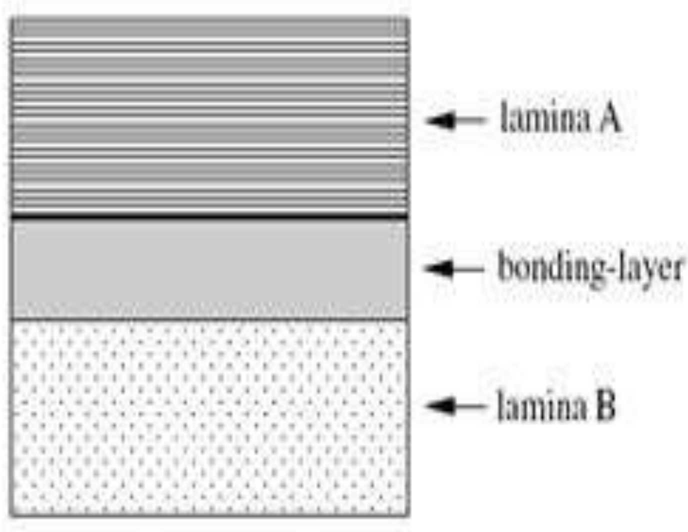

Figure 1.2 Sketch of the interface.

For structures prone to impacts or minor objects drop during assembly or maintenance operation, composite laminates show a very brittle behavior and can undergo serious damages such as matrix cracks, fibers breakages or delamination. These damages are severe because they drastically reduce the mechanical characteristics of the laminate and at the same time can leave visible marks onto the impacted surface. The understanding of the interface imperfection effect on laminated composite plates is of great importance in order to enable designers to improve the plate's strength. Since the most common failure mode in laminated composite plates is delamination at the interface between the adjacent laminates, the effect of imperfect bonding should be taken into consideration in analysis and design.

1.2 Problem Statement

For composite materials, the interface condition between the laminate plays a very important role in the determination of the behavior of the composite laminates. Most of the previous studies on laminated composite were carried out by adopting the assumption that the laminas were perfectly bonded together. However, some researchers have been studying the behavior of composite laminates with interlaminar imperfections.

In most cases, imperfect bonding results in delamination. Delamination is characterized as an insidious separation developed between laminas without being seen on the surface. However, it is possible to detect delamination in the composite material by using advanced techniques such as ultrasonic testing method (Collins, 2009).

It has been proven that the shape of a flat laminated plate subjected to a small impact load in the transverse direction remains flat and in a state of equilibrium. As the applied load gradually increases, small initial discontinuity starts to propagate within the interface between adjacent laminates and results in a significant area of delamination at the interface. When the magnitude of the impact load reaches maximum, the configuration of the plate becomes unstable and the laminate starts to fail (Yousefi et al, 2007).

As mentioned previously, most of the researches done so far are based on the assumption that the interface of the composite plate is perfectly bonded. Currently, there exists only a few studies that handle local interface imperfection problem. In addition, the consideration is either at one location or total separation. Therefore, it would be of great importance to study the behavior of the composite plate with local imperfect interface subjected to impact loads.

1.3 Objective of the Study

The objectives of the study are:

1. To study the behavior of the laminated composite plates with a localized delaminated interface when subjected to impact load for various fiber orientations by means of finite element model.
2. To simulate the response due to the damage of the laminated composite plates when impacted as that of Naik's et al (2006).

1.4 Scope of the Study

The study is restricted to a rectangular laminate plate. The laminate plate is considered to be thin and flat. It consists of two layers of lamina with equal thickness and an interface layer between them. Each lamina is formed by unidirectional fibers of E-glass and the matrix material is Epoxy (3501-6) with a volume fraction of 0.4. The top layer of the lamina comprises fiber that varies in orientation from 0° to 90° and the bottom layer of lamina comprises 0° fiber direction.

In this study, the lamina is considered as a transversely isotropic solid material. By using a finite element method, the plate is modeled as a combination of two laminas with the same boundary condition and thickness using Kirchoff's Classical Laminate Theory. Each node of the plate has five degrees of freedom, which include displacement in *x*-direction (*u*), displacement in *y*-direction (*v*), displacement in *z*-direction (*w*), rotation about *y*-direction ($Ø_x$) and rotation about *x*-direction ($Ø_y$).

The interface layer between the two laminas is modeled as an orthotropic material with zero normal stresses in *x* and *y*-directions ($\sigma_x = 0$ and $\sigma_y = 0$) and zero in-plane shear stress in *x*-*y* plane ($\tau_{xy} = 0$). The interface layer is modeled using quadrilateral zero-thickness solid element with 8 nodes. Each node only considers three degrees of freedom including displacement in *x*-direction (*u*), displacement in *y*-direction (*v*), and displacement in *z*-direction (*w*). The stiffness matrices of the laminas and interface element are computed using 2 by 2 Gauss quadrature rule. The study only considers the impact of low velocity applied at the center of the plate with fully clamped boundaries at all edges. In addition, this study does not take into consideration the damping effect of the system.

1.5 Significance of the Study

For the last few decades, the application of laminated composite materials such as plates and shells has been a point of interest in the industry of construction. The reason behind that is the variety of properties possessed by laminates due to the fact that they consist of different laminas and they offer mechanical properties that depend on the fiber orientation. A lot of researches and studies have been investigating the properties, behavior, strengths, and weaknesses of these laminated composite materials resulting in tremendous advances in this field. However, there is still a lot to investigate about these materials in order to optimize their usage in the construction industry. One of the fields that still needs to be studied deeply is the behavior of the laminated composite plates with local imperfect interface layer subjected to impact loading. Generally, the composites are used in the form of relatively thin plate. Therefore, load carrying capacity of laminated composite plate with imperfect interface against impact is one of the significant concerns in the stability analysis of a laminate structure. That is because most of the previous studies were conducted with the assumption that the laminas are perfectly bonded and no manufacturing defects. This assumption is inadequate since the interface layer has imperfections due to the lamination process during manufacturing. Therefore, the modeling of a laminated composite plate by considering imperfect interface will give more accurate and better approach to the real behavior.

Finally, using finite element method to model such a complex behavior offers a very convenient solution which saves time and effort. This behavior is considered complex because it involves dynamic analysis due to impact loading.

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