# DAMAGE IN LAMINATED COMPOSITES UNDER LOW VELOCITY IMPACT

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**In the name of Allah, Most Gracious, Most Merciful**

To my beloved father and mother

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# ABSTRACT

Composite materials are widely used in aircraft, automotive, marine and railway applications and may be exposed to impact loads, particularly low velocity impact. As material properties of composites are sensitive to strain-rate effects, conducting finite element analysis (FEA) of the impact simulation by using static material properties would not predict their behaviour accurately. Thus, the aim of this study is to incorporate strain-rate dependent behaviour influence into anisotropic damage model (ADM) and implement it in FEA for impact simulation. The study begins with extracting material properties data for ADM from published experimental data. The mathematical equation established from the extracted material properties were then used to develop the strain-rate dependent ADM and coded using ABAQUS/VUSDFLD, commercial finite element software. The developed strain-rate dependent (SRD) ADM was validated using published tensile test data. Impact simulation was conducted using both the static ADM and strain-rate dependent ADM and the results from the simulations were compared with published three-point bending impact experimental data at impactor speeds of 2, 3, 4 and 5 m/s for both cross-ply and angle-ply laminate orientations. The impact simulation results show that the incorporation of strain-rate dependency in ADM improves the prediction of three-point bending impact simulation reaction force by reducing the mean error from 33% to 14% for cross-ply laminates and from 12% to 10% for angle-ply laminates. This strain-rate dependent ADM impact simulation could thus be implemented as a design tool for analysing the impact damage resistant of laminated composites under low velocity impact.

# ABSTRAK

Bahan komposit telah banyak digunakan dalam bidang pesawat terbang, automotif, marin dan kereta api dan mungkin terdedah kepada bebanan impak, terutamanya impak berhalaju rendah. Disebabkan sifat-sifat bahan komposit yang sensitif kepada kesan kadar-terikan, pelaksanaan analisis unsur terhingga (FEA) untuk simulasi impak dengan menggunakan sifat-sifat bahan statik tidak dapat menjangkakan perlakuannya dengan tepat. Oleh itu, tujuan kajian ini adalah untuk menggabungkan pengaruh perlakuan bersandarkan terikan-ricih ke dalam model kerosakan anisotropik (ADM) dan melaksanakannya di dalam FEA untuk simulasi impak. Kajian dimulakan dengan mendapatkan data sifat-sifat bahan untuk ADM daripada data ujikaji yang telah diterbitkan. Persamaan matematik yang dibangunkan daripada sifat-sifat bahan yang diperolehi kemudiannya digunakan untuk membangunkan ADM bersandarkan kadar-terikan (SRD) dan diaturcarakan menggunakan perisian unsur terhingga komersial, ABAQUS/VUSDFLD. ADM bersandarkan kadar-terikan yang dibangunkan ditentusahkan menggunakan data ujian tegangan yang diterbitkan. Simulasi impak telah dijalankan dengan menggunakan kedua-dua ADM statik dan ADM bersandarkan kadar-terikan dan keputusannya telah dibandingkan dengan data eksperimen impak lenturan tiga titik pada kelajuan penghentak 2, 3, 4 dan 5 m/s untuk lamina berorientasi silang and berorientasi sudut. Keputusan simulasi impak yang menggunakan ADM bersandarkan kadar-terikan didapati memberikan jangkaan daya tindak balas simulasi impak lenturan tiga titik yang lebih baik dengan mengurangkan ralat purata dari 33% ke 14% untuk lamina berorientasi silang dan dari 12% ke 10% untuk lamina berorientasi sudut. Simulasi impak yang menggunakan ADM bersandarkan kadar-terikan ini diharap dapat digunakan sebagai alat reka bentuk untuk menganalisis ketahanan daripada kerosakan disebabkan impak halaju rendah terhadap komposit berlamina.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| 3PB | - | Three-point bending |
| ADM | - | Anisotropic damage model |
| BVID | - | Barely visible impact damage |
| DCB | - | Double Cantilever Beam |
| DOF | - | Degree of Freedom |
| CLPT | - | Classical Laminate Plate Theory |
| CZM | - | Cohesive zone model |
| ENF | - | End Notch Flexural |
| ERR | - | Energy Release Rate |
| FEA | - | Finite element analysis |
| FSDT | - | First-order shear deformation theory |
| ISS | - | Interlaminar shear strength |
| MMB | - | Mix Mode Bending |
| PMC | - | Polymer Matrix Composites |
| SRD | - | Strain-rate Dependent |
| UD | - | Uni-directional |
| UTS | - | Ultimate Tensile Strength |
| VCCT | - | Virtual Crack Closure Technique |
| VUSDFLD | - | Vectorized User defined field |

# LIST OF SYMBOLS

$E$ - Young’s modulus
$\sigma$ - Stress
$\sigma^{\mathrm{ult}}$ - Ultimate tensile strength
$\sigma_1$ - Normal tress in x-direction
$\sigma_2$ - Normal stress in y-direction
$\tau_{12}$ - In-plane shear stress
$\varepsilon_{11}$ - Normal strain in x-direction
$\varepsilon_{22}$ - Normal strain in y-direction
$\gamma_{12}$ - In-plane shear strain
$v$ - Poisson’s ratio
$\dot{\varepsilon}$ - Strain rate
$M_X$ - Moment per unit width
$N_X$ - Force per unit width
$\varepsilon^{o}$ - Middle-surface strain
$k$ - Middle-surface curvature
$X^T$ - strength in fiber direction under tension
$X^C$ - strength in fiber direction under compression
$Y^T$ - strength normal to fiber direction under tension
$Y^C$ - strength normal to fiber direction under compression
$S^L$ - in-plane shear strength
$S^T$ - transverse shear strength
$\alpha$ - coefficient that determines the contribution of the shear stress to the fiber tensile initiation criterion $(0< \alpha<1)$
$\delta_{eq}$ - Equivalent displacement
$L_C$ - characteristic length
$\sigma^{O}{}_{eq}$ - Equivalent stress at failure onset
$a$ - crack length

$b$ - Specimen width

$\delta^{O}{}_{eq}$ - Equivalent separation at failure onset

$\delta^{f}{}_{eq}$ - Equivalent separation at damage

$d$ - Damage variable

$E_O$ - Initial Young's modulus

$C$ - Compliance

$G$ - Energy release rate

$G_{IC}$ - Critical strain energy release rate in shear mode I

$G_{IIC}$ - Critical strain energy release rate in shear mode II

$G_{IIIC}$ - Critical strain energy release rate in shear mode III

$G_{TC}$ - Total critical strain energy release rate

$K_n$ - Stiffness in normal mode

$K_t$ - Stiffness in shear mode II

$K_s$ - Stiffness in shear mode III

$N$ - Cohesive element normal stress

$T$ - Cohesive element shear stress at direction-1

$S$ - Cohesive element shear stress at direction-2

$\beta$ - BK mixed-mode parameter

$U_x$ - Displacement in axis-X

$U_y$ - Displacement in axis-Y

$U_z$ - Displacement in axis-Z

$UR_x$ - Rotation about axis-X

$UR_y$ - Rotation about axis-Y

$UR_z$ - Rotation about axis-Z

$\tau_{13}$ - Shear stress at direction-13

$\tau_{23}$ - Shear stress at direction-23

$\sigma_{33}$ - Normal stress at direction-33

$\mu$ - Coefficient of friction

$E$ - Kinetic energy

$m$ - Mass

$V$ - Velocity

$P$ - Loading

$\eta$ - Empirical Constant

$G_c^{ft}$ - Critical energy release rate in fibre direction under tensile loading

$G_c^{fc}$ - Critical energy release rate in fibre direction under compression loading

$G_c^{mt}$ - Critical energy release rate in matrix direction under tensile loading

$G_c^{mc}$ - Critical energy release rate in matrix direction under compression loading

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# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Laminated composites are more becoming the material of choice in advanced engineering applications such as aerospace, marine, automotive and railways due to its advantages such as high strength to weight ratio, resistance to corrosion and low coefficient of thermal expansion when compared to conventional materials, e.g. aluminium, alloys and steel.

The use of laminated composites in advanced engineering applications exposes them from low velocity to high velocity impact loadings during maintenance and operation. Low velocity impact loads induce failure and damage within the lamina and inter-laminar layer (Broutman and Rotem, 1975). Within the lamina layer impact induces matrix cracks and fibre breakage. In addition, at interlaminar layer impact load induces delamination mode of failure or barely visible impact damage (BVID) due to laminated composites' low interlaminar shear strength (ISS). Miller *et al.* (1994) reported that 60% of all damage observed on civil aircrafts is delamination failure caused by impact load. BVID may appear to be undamaged on laminated composite surface during visual inspection; however internal delamination could become an invisible threat since it reduces stiffness and strength of laminated composite structures.

In the last few decades, finite element analysis (FEA) has become an important tool in assisting the design of laminated composites under low velocity impact loads. However, the analysis of low velocity impact load using static material properties (low strain-rate behaviour) of laminated composites was reported to predict impact force 30-40% lower than actual (Okoli and Abdul-Latif, 2002). The underestimate of impact force can be associated with the lack of strain rate-dependant behaviour in laminated composite damage model used. A study by Abrate (1994) indicated that laminated composite structures under low velocity impact of up to 10 $ms^{-1}$ produce strain-rates as high as $10^3$ $s^{-1}$ at the point of impact and $10^1$ $s^{-1}$ elsewhere in the structure. For glass fibre laminated composites, Okoli (1996) reported from the experiments done to relate material properties to strain-rate and concluded that the tensile stiffness and strength increases linearly with log of strain-rate by 1.82% and 9.3% respectively for up to $10^1$ $s^{-1}$ strain-rate. The increase in stiffness and strength of laminated composite is influenced by viscoelastic effect (increase in matrix yield) and matrix non-linear plasticity (Okoli, 1996). Thus, the influence of strain rate-dependant behaviour on simulation of laminated composites under low velocity impact must not be neglected if reliable modeling approaches are to be used.

## 1.2 Problem Statement

Since laminated composites are very vulnerable to impact loads due to its weak interlaminar shear strength, accurate predictive methods are essential in the design of composite structures. The finite element analysis has become a useful tool in the design of laminated composite structures to achieve the required specifications for advanced engineering purposes. However, most finite element analysis for impact simulation lacks the capability to simulate the strain-rate-dependent behaviour of composites. Inclusion of strain-rate-dependent behaviour in finite element models allows better prediction of the impact event and response, enabling optimised design of composite structures with thinner laminates to save weight and reduce production costs.

## 1.3 Objective

The objectives of this study are:

1. To extend an existing anisotropic damage model (ADM) formulation by including strain-rate dependent behaviour for impact simulation.
2. To validate the extended ADM with published experimental data, and to demonstrate the new subroutine capabilities by comparing the results of its simulation of actual impact events with that of the existing ADM.

## 1.4 Scope of Work

The scope of this study cover the following:

1. Linear regression method was used to establish mathematical formulation from published experimental data.
2. Shell element with anisotropic damage model (ADM) and cohesive element with cohesive zone model (CZM) were selected to model the laminated composite. Both elements use bi-linear curve law.
3. The developed strain-rate dependent ADM (SRD ADM) was limited for strain-rate at range between $10^{-3}$ $s^{-1}$ to $10^{5}$ $s^{-1}$.
4. Only tensile test data at strain-rate between $10^{-3}$ $s^{-1}$ to $10^{5}$ $s^{-1}$ was used to validate the developed SRD ADM.
5. Impact simulations were run for impactor speed at range between 2 to 5 $ms^{-1}$.

## 1.5 Thesis Outline

This thesis consists of 6 chapters. In Chapter 1, the background and the necessity of the research are brought out. The issue of laminated composite reliability being faced in the advance engineering applications and the related need for a key of solution are elaborated. The objectives, scope and problem statement of this research are presented.

In Chapter 2, reviews are presented on the laminated composites, failure in laminated composites, low velocity impact failure in laminated composites, effect of strain-rate to laminated composites material properties, finite element analysis of laminated composites, modeling failure and damage at lamina layer and inter-laminar layer.

In Chapter 3, the research methodology is presented. The details of the FEA model and anisotropic damage model (ADM) used in the study are described.

In Chapter 4, the subroutine of strain-rate dependent ADM is presented. The flowchart, mathematical formulation and validation are described. The details on the finite element analysis (FEA) impact simulation models used in the study such as geometry, material properties, boundary conditions and loadings are described.

In Chapter 5, the influence of strain-rate dependent ADM to impact simulation is examined. The damage at the lamina layer and the inter-laminar layer is investigated.

In Chapter 6, conclusions of the research are presented with summary on major findings in the study. Future works for refining the research are recommended.

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