

複合材料積層板與應變率有關之非線性行為

學生：王漢偉

指導教授：蔡佳霖

國立交通大學機械工程研究所

摘要

本研究在建立一理論模型以描述複合材料積層板於不同應變率下其非線性的應力-應變關係。利用單參數塑性能導入流速定理，來建立單方向複合材料在不同應變率下機械行為之黏塑性模型。而此一黏塑性模型係利用冪次函數型式之有效應力-有效塑性應變曲線表示之。結合古典積層板理論，並考慮在積層板各層中之熱殘餘應力，延伸此黏塑性模型，以預測複合材料層板隨應變率變化之非線性行為。將對稱的玻纖/環氧樹脂複合積層板($[\pm 45/90_2]_{4s}$, $[75_2/-60/30]_{4s}$, 與 $[60_2/-75/15]_{4s}$) 與碳纖/環氧樹脂複合積層板($[\pm 45]_{3s}$, $[60/-30]_{3s}$, $[\pm 60]_{3s}$, 與 $[\pm 30]_{3s}$) , 在三個不同之應變率(0.0001/秒 , 0.01/秒 , 與 1/秒) 下作拉伸試驗，用以和理論模型預測比對。

Nonlinear Rate Dependent Behavior of Composite Laminates

Student: Hamvey Wang

Advisor: Jialin Tsai

Institute of Mechanical Engineering

National Chiao Tung University



Abstract

The study aims to investigate and model the strain rate effect on the nonlinear behaviors of composite laminates. The viscoplasticity model proposed for describing the nonlinear rate-dependent behavior of unidirectional composites was employed together with the laminated plate theory to model the rate sensitivity of the composite laminates. It was also considered the thermal residual stress in each ply of laminate. Using one parameter plastic potential to describe the flow rule, this viscoplasticity model was expressed as a single master effective stress-effective plastic strain curve which can be expressed in the form of power law. Two composite laminate materials, symmetric glass/epoxy laminates ($[\pm 45/90]_{2s}$, $[75_2/-60/30]_{4s}$, and $[60_2/-75/15]_{4s}$) and symmetric graphite/epoxy laminates ($[\pm 45]_{3s}$, $[60/-30]_{3s}$, $[\pm 60]_{3s}$, and $[\pm 30]_{3s}$), were tested at three strain rates of 0.0001/s, 0.01/s and 1/s respectively and the experimental results were then compared with the model predictions.

誌謝

時光飛逝，短短兩年的研究生生涯轉眼就過去了。首先感謝指導教授蔡佳霖博士的諄諄指導與教誨，使我順利完成學業與論文，在此致上最誠摯的謝意。而老師指導學生時豐富的專業知識，嚴謹的治學態度以及待人處事方面，亦是身為學生的我學習與景仰的典範。

在論文寫作上，感謝清華大學動機系葉孟考教授、明安國際企業朱國棟博士在百忙中撥冗閱讀並提出寶貴的意見，使得本文的內容更趨完善與充實，在此本人致上無限的感激。

在此並感謝工研院材料所提供實驗需要之設備儀器，以及明安國際企業提供實驗之材料，讓本研究能夠順利進行，得到可靠的實驗結果。

很高興能夠與黃仁傑同學在這兩年的日子裡共同努力，互相切磋討論，每在烏雲蔽空時，得以撥雲見日，另外學弟郭濬清、許世民、陳奎翰生活上的朝夕相處與砥礪磨練，都是我得以完成研究的一大助因，在此由衷地感謝他們。

能有此刻，我也要感謝所有在精神上給我鼓舞支持的人，謝謝各位的幫忙與鼓勵。最後僅以此篇論文，獻給我摯愛的父母王仙法先生、梁小盃女士、妹妹王涵萱、弟弟王育偉。今天我能順利取得碩士學位，要感謝的人很多，上述名單恐有疏漏，在此也一致上我最深的謝意。

Table of Contents

摘要.....	i
Abstract.....	ii
誌謝.....	iii
Table of Contents.....	iv
List of Tables.....	vi
List of Figures.....	vi
I. Introduction.....	1
1.1 Research Motive.....	1
1.2 Paper Review.....	1
1.3 Research Approach.....	4
II. Theory and Method.....	5
2.1 Viscoplasticity Model.....	5
2.2 Constitutive Relations of Unidirectional Composites.....	8
2.3 Numerical Analysis for Off-Axis Composites.....	10
2.4 The Laminated Plate Theory.....	11
2.5 Numerical Analysis for Composite Laminates.....	12
III. Setup of Experiments.....	15
3.1 Experimental Procedure of Tension Tests.....	15
3.1.1 Experimental Setup.....	15
3.1.2 Off-Axis Tests.....	16
3.1.3 Parameter Evaluation.....	17
3.1.4 Tests Results for Composite Laminates.....	18
3.2 Measurement of Thermal Expansion Coefficients of Composites.....	18
3.2.1 Principle of the Measurement Technique.....	19

3.2.2	Correction of the Error from Transverse Sensitivity.....	20
3.2.3	Measurement Procedures and Results.....	22
IV.	Results of Prediction and Discussion.....	24
4.1	Model Predictions for Off-Axis Composites.....	24
4.2	Model Predictions for Composite laminates.....	24
4.3	Effect of Deformation-Induced Change of Fiber Orientation.....	25
4.4	Sensitivity in Stacking Sequence for Symmetric Laminate.....	26
V.	Conclusion.....	27
	Reference.....	28
	Appendix.....	31
A.	Thermal Residual Stresses in Composite Laminates.....	31
B.	Numerical Code.....	33



List of Tables

Table 1. Material constants for glass/epoxy composites.....	41
Table 2. Material constants for graphite/epoxy composites.....	41

List of Figures

Figure 2.1 Orthotropic lamina with principal and off-axis coordinate systems.....	42
Figure 2.2 Flow chart of the numerical analytic procedure for off-axis composite laminae.....	43
Figure 2.3 example of stress-time for laminate tensile test.....	44
Figure 2.4 Flow chart of the numerical analytic procedure for composite laminates.....	45
Figure 2.5 the effective plastic strain rate versus time history diagram of $[\pm 30]_{3s}$ graphite/epoxy at strain rate 0.0001/s.....	46
Figure 3.1 Curing process for graphite/epoxy composite prepreg.....	46
Figure 3.2 Schematic for tension testing system.....	47
Figure 3.3 Dimensions of tensile test specimen.....	48
Figure 3.4 Experiment on the MTS 810 machine.....	48
Figure 3.5 Stress-stain curves for glass/epoxy at 0.0001/s.....	49
Figure 3.6 Stress-stain curves for glass/epoxy at 0.01/s.....	49
Figure 3.7 Stress-stain curves for glass/epoxy at 1/s.....	50
Figure 3.8 Stress-stain curves for graphite/epoxy at 0.0001/s s.....	50
Figure 3.9 Stress-stain curves for graphite/epoxy at 0.01/s.....	51
Figure 3.10 Stress-stain curves for graphite/epoxy at 1/s.....	51
Figure 3.11 Effective stress-effective plastic stain curve for glass/epoxy at 0.0001/s.....	52
Figure 3.12 Effective stress-effective plastic stain curve for glass/epoxy at 0.01/s.....	52

Figure 3.13	Effective stress-effective plastic stain curve for glass/epoxy at 1/s	53
Figure 3.14	Effective stress-effective plastic stain curve for graphite/epoxy at 0.0001/s....	53
Figure 3.15	Effective stress-effective plastic stain curve for graphite/epoxy at 0.01/s.....	54
Figure 3.16	Effective stress-effective plastic stain curve for graphite/epoxy at 1/s.....	54
Figure 3.17	Three master curves by power law curve fitted for glass/epoxy.....	55
Figure 3.18	Three master curves by power law curve fitted for graphite/epoxy.....	55
Figure 3.19	The rate dependent amplitude A -effective plastic stain rate relation on a log-log plot for glass/epoxy.....	56
Figure 3.20	The rate dependent amplitude A -effective plastic stain rate relation on a log-log plot for graphite/epoxy.....	56
Figure 3.21	Stress and strain curve for $[\pm 45/90_2]_{4s}$ glass/epoxy laminates at various strain rates.....	57
Figure 3.22	Stress and strain curve for $[75_2/-60/30]_{4s}$ glass/epoxy laminates at various strain rates.....	57
Figure 3.23	Stress and strain curve for $[60_2/-75/15]_{4s}$ glass/epoxy laminates at various strain rates.....	58
Figure 3.24	Stress and strain curve for $[\pm 45]_{3s}$ graphite/epoxy laminates at various strain rates.....	58
Figure 3.25	Stress and strain curve for $[60/-30]_{3s}$ graphite/epoxy laminates at various strain rates.....	59
Figure 3.26	Stress and strain curve for $[\pm 60]_{3s}$ graphite/epoxy laminates at various strain rates.....	59
Figure 3.27	Stress and strain curve for $[\pm 30]_{3s}$ graphite/epoxy laminates at various strain rates.....	60
Figure 3.28	Half-bridge circuit for measuring thermal expansion coefficient.....	61

Figure 3.29	Schematic for a strain gage subjected to a biaxial strain field.....	62
Figure 3.30	Specimen and reference material placed in the oven for measurement.....	63
Figure 3.31	Thermal expansion response in the axial direction for glass/epoxy composite.....	63
Figure 3.32	Thermal expansion response in the transverse direction for glass/epoxy composite.....	64
Figure 3.33	Thermal expansion response in the axial direction for graphite/epoxy composite.....	64
Figure 3.34	Thermal expansion response in the transverse direction for graphite/epoxy composite.....	65
Figure 4.1	Model predictions and experimental results of stress and strain curve for off-axis glass/epoxy composite at strain rate of 0.0001/s.....	65
Figure 4.2	Model predictions and experimental results of stress and strain curve for off-axis glass/epoxy composite at strain rate of 0.01/s.....	66
Figure 4.3	Model predictions and experimental results of stress and strain curve for off-axis glass/epoxy composite at strain rate of 1/s.....	66
Figure 4.4	Model predictions and experimental results of stress and strain curve for off-axis graphite/epoxy composite at strain rate of 0.0001/s.....	67
Figure 4.5	Model predictions and experimental results of stress and strain curve for off-axis graphite/epoxy composite at strain rate of 0.01/s.....	67
Figure 4.6	Model predictions and experimental results of stress and strain curve for off-axis graphite/epoxy composite at strain rate of 1/s.....	68
Figure 4.7	Model predictions and experimental results of stress and strain curve for $[\pm 45/90_2]_{4s}$ glass/epoxy laminates at various strain rates.....	68
Figure 4.8	Model predictions and experimental results of stress and strain curve for	

	$[75_2/-60/30]_{4s}$ glass/epoxy laminates at various strain rates.....	69
Figure 4.9	Model predictions and experimental results of stress and strain curve for $[60_2/-75/15]_{4s}$ glass/epoxy laminates at various strain rates.....	69
Figure 4.10	Model predictions and experimental results of stress and strain curve for $[\pm 45]_{3s}$ graphite/epoxy laminates at various strain rates.....	70
Figure 4.11	Model predictions and experimental results of stress and strain curve for $[60/-30]_{3s}$ graphite/epoxy laminates at various strain rates.....	70
Figure 4.12	Model predictions and experimental results of stress and strain curve for $[\pm 60]_{3s}$ graphite/epoxy laminates at various strain rates.....	71
Figure 4.13	Model predictions and experimental results of stress and strain curve for $[\pm 30]_{3s}$ graphite/epoxy laminates at various strain rates.....	71
Figure 4.14	Fiber orientation change due to deformation.....	72
Figure 4.15	Model predictions and experimental results for $[\pm 30]_{3s}$ graphite/epoxy laminates at 0.0001/s. Fiber orientation change was considered.....	72
Figure 4.16	Model predictions for $[\pm \theta]_s$ graphite/epoxy laminates at 0.0001/s.....	73
Figure 4.17	Fiber angle of each ply for $[\pm 30]_{3s}$ graphite/epoxy laminate.....	74
Figure 4.18	New model predictions and experimental results of stress and strain curve for $[\pm 30]_{3s}$ graphite/epoxy laminates at various strain rates. Fiber orientation change was considere.....	75