

Thermomechanical and Transformational Behaviour  
and Applications of Shape Memory Alloys and their  
Composites

Kelly Ann Tsoi



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*For my family, with love*

# Declaration of Originality

This thesis describes work that was carried out in the School of Aerospace, Mechanical and Mechatronic Engineering at the University of Sydney, the Aeronautical and Maritime Research Laboratory, Melbourne and at the Department of Metallurgy and Materials Engineering at the Katholieke Universiteit Leuven in Belgium. Except where otherwise acknowledged, the work presented for this degree is my own and contains no material which has been presented for a degree at this or any other university and, to the best of my knowledge and belief, contains no copy or paraphrase of work published by another person, except where duly acknowledged in the text.

Significant contributions are as follows:

Due acknowledgment is given to Dr Rudy Stalmans, Dr Jan Schrooten and Dr Yanjun Zheng for the many useful discussions that were had for the work shown in Chapters 2, 3 and 4 and Dr Xiaoming Wang for the work shown in Chapter 5. The data collection for the SMA wire experiments shown in Chapter 3 was carried out by Dr Gidnahalli Dayanunda and some of the data for the SMA-composite experiments was collected by Dr Yanjun Zheng.

Kelly Ann Tsoi

Melbourne, Australia

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# Synopsis

This thesis details an investigation into the properties and applications of shape memory alloy (SMA) composites. SMA-composites are a new material which have the possibility of having a large impact on what the structures as we know today, are constructed with. SMA-composites are adaptive materials which can be used to control the shape and frequencies of vibration of a structure. In order to determine the effectiveness of such a material, research into the functional properties of SMAs and SMA-composites was conducted.

As an initial step, the transformation behaviour of constrained SMAs was investigated in order to obtain a better understanding into the recovery stress generation of these wires when embedded into a composite material. It is known that the transformation is based on two types of martensite within the alloy; self accommodating and preferentially oriented martensite. The amounts of each type and how they vary with differing pre-strain were determined through DSC measurements and an explanation for why preferentially oriented martensite is not observed during DSC testing was made.

The next step was to investigate the effectiveness of embedding SMA wires into composites and the thermomechanical properties of the SMA wires and the SMA-composites were determined. This was completed using a specially designed tensile testing machine which was capable of having the whole specimen immersed into an oil bath and heated and cooled repeatedly. The stress-strain, strain-temperature, stress-temperature, resistance-strain and cyclic properties of various wires were obtained, giving a better understanding of the behaviour of SMA wires under different test con-

ditions. NiTiCu SMA wires were embedded into kevlar composite materials and the recovery stress generation (stress-temperature), stress-strain, and strain-temperature behaviour was determined.

If SMA-composites are to be used as new materials for structural applications, verification that the embedment of pre-strained SMA wires into the material doesn't adversely affect the impact behaviour needs to be carried out. SMA-composite specimens with varying volume fractions of superelastic SMA wires, pre-strain and position through the thickness were made up for impact damage characterisation. These specimens were impacted at three different energy levels. The results showed that by embedding SMA wires into composite materials there is a reasonably low damage accumulation after impact. There is also no adverse impact effect on the structure compared with structures without wires as well as structures with other types of wires such as steel and martensitic SMA wires. The SMA-composites showed good damping and energy absorption capabilities.

A novel application of SMA-composites is their use as a SMA patch in order to repair damage in existing cracked metallic structures. An analytical study and finite element modelling showing the closure stresses obtainable for use as patches was made.

*'The most exciting phrase to hear in science, the one that heralds new discoveries, is not "Eureka!" but rather "hmmm....that's funny..." '*

Isaac Asimov

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*Praise the Lord,  
Give thanks to the Lord, for he is good;  
his love endures forever  
Psalm 106:1*

# List of Publications

Below is a list of publications which have been made related to the work completed in this PhD.

## **International Refereed Journals**

### **First author:**

1. K.A. Tsoi, R. Stalmans and J. Schrooten, "Transformation Behaviour of Constrained Shape Memory Alloys", *Acta Materialia*, **50**, 14, pp. 3535-3544, September 2002.
2. K.A. Tsoi, R. Stalmans, J. Schrooten and Y.-W. Mai, "Impact Damage Behaviour of Shape Memory Alloy Composites", *Materials Science and Engineering: A*, **342**, 1-2, pp. 207-216.

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1. Y.J. Zheng, J. Schrooten, K. Tsoi and R. Stalmans, "Thermal Response of Glass Fiber/Epoxy Composites with Embedded TiNiCu Alloy Fibers", *Materials Science and Engineering: A*, **335**, 1-2, pp. 157-163, 25 September 2002.
2. Y.J. Zheng, J. Schrooten, K. Tsoi and P. Sittner, "Qualitative and Quantitative Evaluation of the Interface in Activated SMA-Composites", *Experimental Mechanics*, submitted 2001.

**Conference Proceedings****First author:**

1. K.A. Tsoi, R. Stalmans, M. Wevers, J. Schrooten and Y.-W. Mai, "Increased Impact Damage Resistance of Shape Memory Alloy Composites", Proceedings of SPIE, Smart Materials and MEMS, 13-15 December, Melbourne, Australia, Alan R. Wilson; Hiroshi Asanuma (Eds.), 4234, pp. 126-134, 2000.
2. K. A. Tsoi, X. Wang, Y.-W. Mai and S.C. Galea, "Life Enhancement and Repair of Structures using Shape Memory Alloy Composite Patches", ICCM-12 Conference, Paris, July 1999, paper 468, (CD-Rom), ISBN 2-9514526-2-4.
3. K.A. Tsoi, X.M.Wang, Y-W. Mai, and S.C. Galea, "The Use of Shape Memory Alloy Patches as a Repair Technique", Proceedings of the Aust. Fracture Group: Structural Integrity and Fracture Meeting, C.H. Wang (Ed.), pp. 33-41, 1998.

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1. J. Schrooten, K.A. Tsoi, R. Stalmans, Y. Zheng and P. Sittner, "Comparison Between Generation of Recovery Stresses in Shape Memory Wires and Composites: Theory and Reality", Proceedings of SPIE, Smart Materials and MEMS, 13-15 December, Melbourne, Australia, Alan R. Wilson; Hiroshi Asanuma (Eds.), 4234, pp. 114-124, 2000.
2. R. Stalmans, K. Tsoi and J. Schrooten, "The Transformational Behaviour of Shape Memory Wires Embedded in a Composite Matrix", Fifth European Conference on Smart Structures and Materials, Glasgow, Scotland, May 22-24, 2000, P.F. Gobin, C.M. Friend (Eds.), Proceedings of SPIE, Vol. 4073, pp. 88-96, 2000.
3. X. Wang, K. Tsoi, L. Ye, Y.-W. Mai, S.C. Galea and L. R. Francis Rose, "SMA Composites for Aero-Structure Repairs", ICCM-12 Conference, Paris, July 1999, paper 620, (CD-Rom), ISBN 2-9514526-2-4.

# Symbols and Abbreviations

Listed here are only the symbols used several times or in a global context. The symbols used locally are explained where they are used.

$A_d$	projected delamination area (mm <sup>2</sup> )
$A_f$	austenitic finish temperature (°C)
$A_m$	cross sectional area of matrix (mm <sup>2</sup> )
$A_p$	austenitic peak temperature (°C)
$A_s$	austenitic start temperature (°C)
$A_{sma}$	cross sectional area of SMA (mm <sup>2</sup> )
$A_T$	total cross sectional area of SMA-composite patch (mm <sup>2</sup> )
$\alpha_s$	coefficient of thermal expansion of the SMA (/°C)
$\alpha_m$	coefficient of thermal expansion of the matrix (/°C)
$d_{min}$	minimum measured displacement of impact head during impact (mm)
$\Delta H_a$	austenitic transformation heat (J/g)
$\Delta H_m$	martensitic transformation heat (J/g)
$\Delta H_r$	R-phase transformation heat (J/g)
$\Delta H_{SAM}$	measured transformation heat due to self accommodating martensite (J/g)
DSC	differential scanning calorimetry
$E_a$	energy absorbed (J or %)
$E_m$	Young's modulus of elasticity of matrix (GPa)
$E_p$	Young's modulus of elasticity of SMA-patch (GPa)
$E_s$	Young's modulus of elasticity of cracked structure (GPa)
$E_{sma}$	Young's modulus of elasticity of SMA (GPa)
$\epsilon_m$	total strain of matrix
$\epsilon_{ma}$	thermal expansion strain of matrix
$\epsilon_{max}$	maximum shape memory strain
$\epsilon_{me}$	elastic strain of matrix
$\epsilon_p$	equivalent pre-strain of SMA-composite patch
$\epsilon_{ps}$	pre-strain of SMA
$\epsilon_{sma}$	total strain of SMA wires
$\epsilon_{sa}$	thermal expansion strain of SMA
$\epsilon_{se}$	elastic strain of SMA
$\epsilon_{sr}$	recoverable shape memory strain
$F_{max}$	maximum force measured on impact (N)

FEM	finite element modelling
$F_r$	recovery force (N)
$F_t$	transferred force (N)
$G_a$	adhesive shear modulus (MPa)
$h_p$	thickness of SMA-composite patch (mm)
$h_s$	thickness of cracked structure (mm)
$l_p$	length of SMA-composite patch (mm)
$M_f$	martensitic finish temperature ( $^{\circ}\text{C}$ )
$M_p$	martensitic peak temperature ( $^{\circ}\text{C}$ )
$M_s$	martensitic start temperature ( $^{\circ}\text{C}$ )
$n_w$	number of embedded wires
POM	preferentially oriented martensite
$R_f$	R-phase finish temperature ( $^{\circ}\text{C}$ )
$R_p$	R-phase peak temperature ( $^{\circ}\text{C}$ )
$R_s$	R-phase start temperature ( $^{\circ}\text{C}$ )
SAM	self accommodating martensite
SIM	stress induced martensite
SMA	shape memory alloy
SME	shape memory effect
$\sigma_c$	closure stress (MPa)
$\sigma_p$	average normal stress of composite patch (MPa)
$\sigma_r$	recovery stress of SMA (MPa)
$\sigma_s$	average normal stress of cracked structure (MPa)
$\sigma_{sma}$	stress of SMA (MPa)
$\tau_a$	shear stress in adhesive (MPa)
$T_g$	glass transition temperature ( $^{\circ}\text{C}$ )
$u_p$	in-plane displacement along x-axis direction of the SMA-patch
$u_s$	in-plane displacement along x-axis direction of the cracked structure
$V_f$	volume fraction of embedded SMA wires (wires/mm)
$w_p$	width of SMA-composite patch (mm)
$w_s$	width of cracked structure (mm)

# Contents

**Declaration**

**Abstract** **i**

**Acknowledgements** **iv**

**Publications** **vii**

**Symbols and Abbreviations** **ix**

**List of Tables** **xii**

**List of Figures** **xiii**

**1 Introduction** **1**

1.1	General Properties of Shape Memory Alloys . . . . .	3
1.1.1	Martensitic Transformations . . . . .	3
1.1.2	One Way Shape Memory Effect . . . . .	5
1.1.3	Degradation Effects of the Shape Memory Effect . . . . .	7
1.1.4	R-Phase Transition . . . . .	7
1.1.5	Superelasticity . . . . .	8
1.1.6	Damping Properties of Shape Memory Alloys . . . . .	13
1.1.7	Two Way Shape Memory Effect . . . . .	14
1.1.8	Ni-Ti and Cu based Alloys . . . . .	15

1.2	Review of Shape Memory Alloys Embedded in Composites and Epoxy Resins . . . . .	16
1.2.1	Interfacial Properties of SMA-Composites . . . . .	17
1.3	Constitutive Modelling of SMAs and SMA-Composites . . . . .	18
1.3.1	Internal Variable Models . . . . .	19
1.3.2	Other Models . . . . .	21
1.3.3	SMA-Composite Constitutive Models . . . . .	24
1.4	Impact Damage of Laminate and Hybrid Composites . . . . .	25
1.4.1	Impact Damage of Composite Laminates: Background . . . . .	25
1.4.2	Influence of Stacking Sequence on Laminate Strength . . . . .	27
1.4.3	Delaminations During Impact . . . . .	28
1.4.4	Impact Damage Size . . . . .	29
1.4.5	Residual Properties of Impact Damaged Composites . . . . .	29
1.4.6	Reduction of Impact Damage in Composites . . . . .	30
1.5	Applications of SMAs . . . . .	32
1.5.1	Shape Memory Alloys for Reinforcement and Shape Control . . . . .	33
1.5.2	Couplings and Fasteners . . . . .	35
1.5.3	Space Applications . . . . .	36
1.5.4	SMA Actuators . . . . .	36
1.5.5	Biomedical Applications . . . . .	36
1.5.6	Vertical Tail . . . . .	38
1.5.7	Ornamental and Other Items . . . . .	38
<b>2</b>	<b>Transformation Behaviour of SMA Wires</b>	<b>40</b>
2.1	Introduction . . . . .	40
2.2	Experimental Techniques . . . . .	41
2.2.1	Materials Used . . . . .	41
2.2.2	Specimen Production . . . . .	43
2.3	Determination of Transformation Temperatures and Transformation Heats	43
2.3.1	Cutting Techniques . . . . .	45

2.3.2	Differential Scanning Calorimetry Experiments . . . . .	46
2.4	Results . . . . .	47
2.4.1	Transformational Behaviour of Constrained SMA Wires . . . . .	47
2.4.2	A Note on Errors . . . . .	52
2.5	Discussion . . . . .	53
2.6	Excursion . . . . .	59
2.6.1	Transformational Behaviour of Unconstrained SMA Wires . . . . .	60
2.7	Conclusion . . . . .	64
<b>3</b>	<b>Thermomechanical Behaviour of SMA Wires and SMA-Composites</b>	<b>65</b>
3.1	Introduction . . . . .	65
3.2	Thermomechanical Testing Machine . . . . .	66
3.3	Materials Used . . . . .	67
3.4	Thermomechanical Behaviour of SMA wires . . . . .	67
3.4.1	Experimental Techniques . . . . .	67
3.5	Results and Discussion . . . . .	73
3.5.1	Stress versus Strain . . . . .	73
3.5.2	Strain versus Temperature . . . . .	77
3.5.3	Resistance versus Strain . . . . .	80
3.5.4	Stress versus Temperature . . . . .	82
3.6	Thermomechanical Behaviour of SMA-Composites . . . . .	93
3.6.1	Specimen Production . . . . .	93
3.6.2	Load Cases Used . . . . .	93
3.7	Results and Discussion . . . . .	94
3.7.1	Recovery Stress Generation . . . . .	94
3.7.2	Stress versus Strain . . . . .	101
3.7.3	Strain versus Temperature . . . . .	107
3.8	Conclusions . . . . .	108
<b>4</b>	<b>Impact Damage Characteristics of SMA-Composites</b>	<b>111</b>
4.1	Impact Damage of SMA-Composites . . . . .	111



4.1.1	Superelastic SMAs . . . . .	113
4.2	Superelasticity . . . . .	113
4.3	SMA-Composite Production . . . . .	113
4.3.1	Matrix Properties . . . . .	113
4.3.2	Shape Memory Alloys Used . . . . .	115
4.3.3	SMA-Composite Assembly . . . . .	116
4.3.4	Problems Encountered During Processing . . . . .	118
4.4	Impact Testing . . . . .	124
4.4.1	Impact Testing Apparatus . . . . .	124
4.4.2	Rate Sensitivity During Impact of Specimens . . . . .	126
4.4.3	Experimental Impact Tests . . . . .	126
4.4.4	Calculation of Experimental Parameters and Correction Factor . . . . .	128
4.5	Analysis Techniques . . . . .	132
4.5.1	C-Scan . . . . .	132
4.5.2	Optical Microscopy . . . . .	134
4.6	Results and Discussion . . . . .	134
4.6.1	Position of the Wires . . . . .	137
4.6.2	Effect of Pre-Strain. . . . .	140
4.6.3	Effect of Varying the Wire Spacing . . . . .	142
4.6.4	Different Wire Types . . . . .	146
4.6.5	Impact Performance Map . . . . .	150
4.7	Conclusion . . . . .	154
<b>5</b>	<b>Shape Memory Alloy Patches for Structural Repair</b>	<b>157</b>
5.1	Introduction . . . . .	157
5.2	Analytical Modelling of a SMA-Composite Patch . . . . .	159
5.3	Results . . . . .	163
5.3.1	Closure Stress . . . . .	164
5.3.2	Variation of Patch Thickness . . . . .	169
5.3.3	Variation of Structure Material . . . . .	170

<i>CONTENTS</i>	xvi
5.4 Finite Element Modelling . . . . .	170
5.5 Results and Discussion of FE Modelling . . . . .	173
5.5.1 Effect of Adhesive Layer on Stress . . . . .	173
5.5.2 Variation of Volume Fraction and Pre-Strain of SMA Wires . . . . .	174
5.6 Conclusion . . . . .	179
<b>6 Conclusion</b>	<b>181</b>
6.1 General Conclusions . . . . .	181
6.2 Prospects for Future Work . . . . .	184
<b>References</b>	<b>186</b>
<b>A Thermomechanical Behaviour of SMA-Epoxy Matrix Composites</b>	<b>203</b>
A.1 Specimen Production . . . . .	203
A.2 Instron Testing Machine . . . . .	205
A.3 Heating of the Specimens Using an Oven . . . . .	205
A.4 Heating of the Specimens Using Electric Current . . . . .	206
A.5 Heating Using Flash Lamps . . . . .	207
A.5.1 Thermal Transfer Calculations of the Temperature Inside the Composite . . . . .	207
A.6 Results and Discussion . . . . .	210
<b>B Refereed Publications</b>	<b>215</b>

# List of Tables

2.1	Table of transformation temperatures . . . . .	42
2.2	Table of transformation heats . . . . .	42
3.1	Description of wires used . . . . .	68
3.2	Transformation temperatures ( $^{\circ}\text{C}$ ) of as-received wires . . . . .	69
3.3	Transformation heats (J/g) of as-received wires . . . . .	69
3.4	Comparison of Young's modulus values of SMA wires . . . . .	74
3.5	Table of maximum plateau strain (%) at different temperatures . . . . .	76
3.6	Table of resistance-strain rate ( $\frac{dR}{d\epsilon}$ ) ( $\Omega$ ). . . . .	82
3.7	Summary of recovery stresses generated by SMA-composites . . . . .	98
3.8	Young's modulus of SMA-composites . . . . .	103
3.9	Material properties of composite components used in theoretical calculations. . . . .	106
3.10	Comparison of experimental and theoretical Young's modulus (11.8% $V_f$ ). . . . .	107
3.11	Summary of the coefficients of thermal expansion for SMA-composites. . . . .	108
4.1	Glass epoxy matrix tensile test parameters and results . . . . .	114
4.2	Details of impact specimens . . . . .	119
4.3	% absorbed energy and maximum measured force during impact (average). . . . .	138
4.4	Minimum measured displacement and damage depth during impact (average). . . . .	139
5.1	Material properties used for analytical calculations. . . . .	163
5.2	Comparison of measured and calculated maximum closure stress . . . . .	167

5.3 Table of experimental and calculated recovery stresses . . . . . 168

5.4 Material properties and closure stress for structures . . . . . 170

5.5 Material properties for FEM . . . . . 172

A.1 Experimental results of forces obtained after heating the SMA-composites.213

# List of Figures

1.1	Schematic representation of (a) the original form and (b) and (c), two crystallographic forms possible during a martensitic transformation. . .	4
1.2	Crystallographic structures found in SMAs. . . . .	5
1.3	The one way shape memory effect. . . . .	6
1.4	Crystallographic overview of the shape memory effect (after Wayman and Duerig, 1990). . . . .	6
1.5	Stress vs Strain characteristics showing superelasticity (after Duerig and Zadno (1990)). . . . .	9
1.6	Stress vs temperature phase diagram showing the temperature range where superelasticity occurs. (After Duerig and Zadno (1990)). . . . .	11
1.7	Two way memory effect. . . . .	15
1.8	(a) Image of the vertical tail produced using a SMA reinforced composite panel and (b) results upon activation of the vertical tail . . . . .	38
2.1	Image of the frame used in the production of the SMA-composite specimens. . . . .	44
2.2	Examples of SMA-composite specimens used in this investigation. . . . .	44
2.3	Chart of comparison between cutting techniques . . . . .	46
2.4	Differential scanning calorimeter curves for composite specimens with embedded NiTi (sms150moh) wires for different pre-strains showing the heating curve . . . . .	47

2.5	Differential scanning calorimetry curves for composite specimens with embedded NiTi (sms150moh) wires for 0% pre-strain showing cooling and heating. . . . .	48
2.6	Stress vs temperature chart showing stable thermal cyclic behaviour for a SMA-composite embedded with NiTiCu (mes150m) wires . . . . .	49
2.7	Transformation temperature as a function of % pre-strain for embedded wires (a) NiTi and (b) NiTiCu (mes150m) wires. . . . .	50
2.8	The measured transformation heats during heating versus the pre-strain for composite samples . . . . .	51
2.9	Stress vs strain curves for NiTi (sms150moh) and NiTiCu (mes150m) wires. . . . .	53
2.10	The recovery stress build up and heat flow vs temperature for a constrained shape memory wire (NiTiCu (mes150m), 3% pre-strain). . . . .	54
2.11	Strain-temperature relationships of elastic and SMA wire strains with temperature. . . . .	58
2.12	(a) DSC curve for NiTi (sms150moh) 5% pre-strained SMA-composite, showing global baseline shift . . . . .	59
2.13	Transformation temperature versus % pre-strain for (a) NiTi (sms150moh) wire ends,(b) NiTi (sms150moh) removed wires . . . . .	61
2.14	Transformation heat versus % pre-strain for (a) NiTi (sms150moh) wire ends, (b) NiTi (sms150moh) removed wires, (c) NiTiCu (mes150m) wire ends and (d) NiTiCu (mes150m) removed wires. . . . .	62
3.1	Tensile testing machine used for testing SMA wires and SMA-composites	66
3.2	Strain vs temperature behaviour of NiTiCu (mes150m) showing the complete cycle. . . . .	72
3.3	Thermal cycle of a NiTiCu (mes150m) wire pre-strained to 3% and heated	72
3.4	Stress versus strain behaviour of (a) NiTiCu (mes150m), (b) NiTiCu (ths150mcu), (c) NiTi-R-phase (ths150r), (d) NiTi (ths150a), (e) NiTi (sms150ao) . . . . .	75

3.5	Stress versus strain behaviour of (a) NiTiCu (mesm150m1) and (b) NiTiCu (mesm150m2) at different temperatures . . . . .	76
3.6	Strain versus temperature behaviour of (a) NiTiCu (mes150m), (b) NiTiCu (ths150mCu), (c) NiTi R-phase (ths150rp) . . . . .	78
3.7	Strain versus temperature behaviour of different wires at a constant load of (a) 141 MPa and (b) 283 MPa. . . . .	79
3.8	Resistance versus strain behaviour of (a) NiTiCu (mes150m) . . . . .	81
3.9	Stress versus temperature for NiTiCu-(mes150m) wires pre-strained to 1%, 3%, and 6% . . . . .	83
3.10	Stress versus temperature for (a)NiTiCu (ths150mCu), (b) NiTi (ths150r), (c) NiTi (ths150a) . . . . .	84
3.11	Stress versus temperature for (a)NiTiCu (ths150mCu), (b) NiTi (ths150r), (c) NiTi (ths150a) . . . . .	85
3.12	Heating and cooling cycle for different wires pre-strained to 3% and heated to 110°C. . . . .	87
3.13	Stress rate versus temperature for different wires. . . . .	88
3.14	Cyclic stress versus temperature for NiTiCu (mes150m) wire pre-strained to 3% . . . . .	89
3.15	Stress versus time long term cyclic behaviour using resistive heating and a current of 700 mA for NiTiCu . . . . .	90
3.16	Stress versus time long term cyclic behaviour for NiTiCu (mes150m) wires cycled using a current of (a) 600 mA, (b) 700 mA, (c) 800 mA and (d) 900 mA . . . . .	91
3.17	Stress versus time long term cyclic behaviour using resistive heating and a current of 700 mA for wires (a) NiTiCu (mes150m), (b) NiTiCu (ths150mCu), . . . . .	92
3.18	Stress versus temperature charts for SMA-composite specimens with NiTiCu wires (2 wires/mm) for (a) reference specimen (no wires) and pre-strains of (b) 1, (c) 2, (d) 3, (e) 4 and (f) 5% . . . . .	95

3.19	Stress versus Temperature charts for SMA-composite specimens with different pre-strain values at (a) 110°C and (b) 140°C. . . . .	96
3.20	Stress versus temperature charts for SMA-composite specimens with (a) reference specimen (no wires) and wires pre-strained to (b) 1%, (c) 2%, (d) 3%, (e) 4% and (f) 5% . . . . .	97
3.21	Stress versus temperature for SMA-composite specimens with wires pre-strained to 3% and heated to 110°C with a wire fraction of 2.95%. . .	100
3.22	Stress versus temperature charts for NiTiCu (mes150m) SMA-composite specimens with wires pre-strained to 3% and thermally cycled to (a) 110°C and (b) 140°C. . . . .	101
3.23	Stress versus strain curves for SMA-composite specimens heated at 25°C, 80°C, 100°C, 120°C and 140°C . . . . .	102
3.24	Comparisons of stress versus strain curves for SMA-composites pre-strained to 1%, 3% and 5% for different temperatures . . . . .	104
3.25	Strain versus temperature charts of NiTiCu SMA-composite embedded with different wire fractions of 2.95%, 5.9% and 11.8% . . . . .	105
3.26	Stress versus strain behaviour of NiTiCu SMA wire at different temperatures. The regions where the modulus values, $E$ and $E_{sma}$ are defined, are also indicated. . . . .	106
4.1	Stress versus strain graph of the superelastic NiTi wire used for the impact specimens. . . . .	116
4.2	Impact specimen dimensions. . . . .	117
4.3	Stress versus strain graph of the glass-fibre epoxy pre-preg used in the impact specimens. . . . .	118
4.4	Steps in the production of specimens. (a) Uncured SMA-composite specimen in aluminium foil envelope. (b) Specimens prepared for curing. .	120
4.5	Example of a prepared specimen. . . . .	121
4.6	Heat flow versus temperature of composite specimens showing different post-cure heat treatment intervals. . . . .	122



4.7	Heat flow versus temperature of the as-received uncured pre-preg and the “under cured” composite. . . . .	122
4.8	Comparison of impact results for post cured and under-cured specimens.	124
4.9	(a) Impact testing apparatus, (b) impact head, and (c) clamping device	125
4.10	Comparison of the rate sensitivity of impact results for heights of 3.4 m/s and 4.7 m/s . . . . .	127
4.11	(a) Force versus time chart and (b) displacement versus time chart for 6, 12 and 18J impacts of specimens with no wires. . . . .	129
4.12	Force and displacement versus time are shown for (a) 18J specimen and (b) 12J specimen. . . . .	131
4.13	Different NDE techniques used to determine damage in structures. (After ESDU, 1991). . . . .	132
4.14	C-scan image of an 18J impacted specimen. . . . .	134
4.15	Histogram of the intensity versus number of pixels obtained from a C-scan of impact damage corresponding to Figure ?? . . . . .	135
4.16	Optical images of the plane view of impacted composite specimens with no wires at 18J, 12J and 6J (looking from the bottom of the specimen) showing the different levels of damage. . . . .	136
4.17	(a) Energy absorbed, (b) maximum measured force, (c) projected damage area and (d) minimum measured displacement versus wire spacing .	140
4.18	Visual images of superelastic SMA-composites with wires . . . . .	141
4.19	Microscope image of SMA wires embedded between (a) $2 \times 45^\circ$ and (b) $45^\circ$ and $0^\circ$ plies . . . . .	142
4.20	(a) Energy absorbed and maximum impact force and (b) delamination area, for different levels of pre-strain of superelastic NiTi wire . . . . .	143
4.21	Visual images of superelastic SMA-composites with wires pre-strained to 3% and with different wire spacings within the specimen . . . . .	145
4.22	(a) Energy absorbed, (b) maximum measured force, (c) projected damage area and (d) minimum measured displacement versus wire type . .	147

4.23	(a) Projected damage area and (b) minimum measured displacement versus absorbed energy for different wire spacing of the wires. . . . .	147
4.24	Damage depth versus minimum measured displacement ( $d_{min}$ ) and projected damage area ( $A_d$ ) for 12J and 18J impacts. . . . .	148
4.25	(a) Maximum measured force and energy absorbed, (b) projected delamination area and (c) minimum measured displacement versus wire type (6J) . . . . .	149
4.26	(a) Maximum impact force and energy absorbed, (b) projected delamination area and (c) minimum measured displacement versus wire type (12J) . . . . .	151
4.27	Damage depth versus (a) incident energy and (b) absorbed energy for different specimen types where the wires are embedded along the bottom of the SMA-composite specimen. . . . .	152
4.28	(a) Projected damage area versus incident energy, (b) absorbed energy versus incident energy. . . . .	153
4.29	Impact performance map. . . . .	153
5.1	Schematic diagram of a cracked metallic structure with a SMA-composite patch applied to the surfaces. . . . .	159
5.2	Schematic diagram of the stresses obtained from each of the elements in the cracked patched structure . . . . .	160
5.3	Closure stress versus pre-strain for varying $V_f$ of SMA wires. The thickness of the patch, $h_p$ , was 0.3 mm. . . . .	164
5.4	Closure stress versus thickness ratio for varying patch ( $h_p$ ) and cracked structure ( $h_s$ ) thickness, for wires pre-strained to 3% for a $V_f$ of 11.8%. . . . .	165
5.5	Closure stress versus thickness ratio for varying volume fraction of SMA wires, pre-strained to 3% and embedded in a patch of thickness 0.3 mm. . . . .	166
5.6	Closure stress versus patch thickness for varying pre-strain of SMA wires embedded in a composite patch and applied to a 10 mm thick Al plate. . . . .	169

5.7	Schematic of the SMA patch attached to an aluminium plate and the one-quarter model used in the FE analysis. . . . .	173
5.8	FEM results showing axial stress at the centre of the aluminium structure and shear stress at the edge of the SMA patch versus thickness of adhesive layer . . . . .	174
5.9	Variation of (a) axial stress at (0,0), (b) shear stress at edge of patch with varying % pre-strain for differing $V_f$ of SMA wires . . . . .	175
5.10	Results of analytically based FEA for varying % pre-strain of SMA wires embedded with a $V_f$ of 11.8% and a patch thickness of 0.3 mm. . . . .	176
5.11	Results of experimentally based FEA for varying % pre-strain of SMA wires embedded with varying $V_f$ and a patch thickness of 0.3 mm. . . . .	177
5.12	Results for varying $V_f$ of SMA wires for analytically based FEA. . . . .	178
A.1	Mould used for SMA wire/epoxy matrix composites; A. top view, B. side view. . . . .	204
A.2	Cured composite with 24 embedded SMA wires. . . . .	204
A.3	SMA wire/epoxy matrix composite with metal end tabs. . . . .	205
A.4	SMA wire/epoxy matrix composite clamped in the tensile testing machine. . . . .	206
A.5	Temperature versus time chart for an epoxy specimen heated using a flash lamp . . . . .	208
A.6	(a) Diagram showing the heat flux onto a specimen and the positioning of the wire. (b) SMA wire/epoxy matrix composite with metal end tabs. . . . .	208
A.7	Temperature versus time chart for an epoxy specimen . . . . .	211
A.8	Temperature and force versus time for a composite embedded with 30 wires . . . . .	212
A.9	Composite temperature and force versus time for (a) a reference composite with no wires and (b) a composite with 26 wires. . . . .	213
A.10	SMA composite shown in grips after heating. There is a permanent twist induced in the specimen. . . . .	214