

Contents

Glossaries	xv
1 Introduction	1
1.1 Motivation	1
1.2 State of the Art	2
1.3 Aim and Structure of the Present Work	7
2 Fundamentals	9
2.1 Continuum Mechanics	9
2.1.1 Kinematics	9
2.1.2 Stress	14
2.2 Polymer Materials Theory	16
2.2.1 Linear Elasticity	16
2.2.2 Hyperelasticity	17
2.2.3 Viscoelasticity	20
2.2.4 Time-Temperature Superposition	26
2.2.5 Numerical Treatment of Viscoelasticity	29
2.2.6 Thermoviscoelasticity	30
2.2.7 Adiabatic Heating	31
2.3 Materials and Laminated Setup	32
2.3.1 Poly(methyl Methacrylate) (PMMA)	32
2.3.2 Thermoplastic Polyurethane (TPU)	38
2.3.3 PMMA-TPU Laminate	41
3 Experimental Investigation	45
3.1 General Experimental Procedures	46
3.1.1 Specimen Preparation	46
3.1.2 Digital Image Correlation	47
3.1.3 Infrared Surface Temperature Measurements	48
3.1.4 Sensors and Signal Processing	49
3.2 Experimental Investigation of PMMA	50
3.2.1 Transient Plane Source Method Experiments	50
3.2.2 Dynamic Mechanical Thermal Analysis	52

3.2.3	Uniaxial Tensile Tests	58
3.2.4	Three-Point Bending Tests	62
3.2.5	Dart Impact Tests	64
3.3	Experimental Investigation of TPU Interlayers	69
3.3.1	Transient Plane Source Method Experiments	69
3.3.2	Dynamic Mechanical Thermal Analysis	70
3.3.3	Uniaxial Tensile Tests	72
3.3.4	Biaxial Tensile Tests	78
3.4	Experimental Investigation of PMMA-TPU Laminates	81
3.4.1	Three-Point Bending Test	81
3.4.2	Clamped Bending Tests	85
3.4.3	Dart Impact Tests	87
3.5	Summary	91
4	Material Modelling of PMMA	93
4.1	Linear Viscoelasticity	94
4.2	Hyper-Viscoelasticity	98
4.3	Thermo-Hyperviscoelasticity	101
4.4	Linear Thermoviscoelasticity Using the Arrhenius Shift Equation	102
4.5	A Simplified Failure Criterion	105
4.6	Summary	108
5	Material Modelling of TPU	109
5.1	Hyperelasticity	109
5.2	Tabulated Hyperelasticity	110
5.3	Hyper-Viscoelasticity	111
5.4	Thermo-Hyperviscoelasticity	113
5.5	Adiabatic Heating	113
5.6	Summary	115
6	Simulation of PMMA-TPU Laminate	117
6.1	FE-Modelling	117
6.1.1	Mesh Structure and Element Types	118
6.1.2	Coincident Element Modelling	118
6.1.3	Tied and Tiebreak Contacts for Delamination Modelling	120
6.2	Mechanical Behaviour	121
6.2.1	Dart Test	121
6.2.2	Global Energy Failure Threshold	122
6.2.3	Clamped Bending Simulations	124
6.3	Temperature Dependent Mechanical Behaviour	125
6.4	Coupled Thermomechanical Behaviour	127

6.5	Summary	129
7	Component Tests and Validation	131
7.1	Experimental Setup	131
7.2	PU Adhesive	133
7.3	Monolithic Materials.....	134
7.4	PMMA-TPU Laminate	136
7.5	Validation of the Finite Element Model.....	137
7.6	Summary	141
8	Summary and Outlook	143
	References and Regulations	145
A	Experiments	157
A.1	Materials used in Experiments	157
A.2	Transient Plane Source Method	157
A.3	Dynamic Mechanical Thermal Analysis.....	159
A.4	Uniaxial Tensile Tests	160
A.5	Three-Point Bending Test	162
A.6	Dart Impact Tests	164
B	Material Modelling	165
B.1	Material Parameters for PMMA.....	165
B.2	Material Parameters for TPU.....	166