



University of Pisa

Department of Civil and Industrial Engineering

Master of Science in Civil Engineering

Experimental and theoretical study on the creep behavior of GFRP pultruded beams

Supervisors:

Prof. Ing. Paolo S. Valvo

Dr. Ioannis Stefanou

Candidate:

Simone Loni

Academic Year 2012 – 2013

Dedico questo lavoro a tutta la mia famiglia, in particolare a chi ci ha da poco lasciato e chi è appena arrivato.

Desidero inoltre ringraziare i miei genitori per avermi dato l'opportunità di trascorrere un periodo di studio a Parigi, il quale ha fortemente contribuito alla realizzazione della tesi.

Ringrazio Livia per essere sempre stata presente e vicina, soprattutto nei momenti di lontananza.

Ringrazio Gianluca per questi anni di frequenti aiuti, valide consultazioni, fruttuosi appunti nonché per la profonda amicizia che ci accomuna.

Vorrei poi ringraziare il Dr. Ioannis Stefanou ed il Prof. Ing. Paolo S. Valvo per avermi proficuamente seguito e consigliato durante la preparazione e stesura della tesi ed inoltre per avermi dato l'opportunità di presentare il mio lavoro al di fuori dell'Università di Pisa.

Then, I would like to thank Dr. Ioannis Stefanou and Prof. Ing. Paolo S. Valvo for helping me usefully during the preparation and writing of this thesis and for the opportunity to present my work beyond the University of Pisa.

Infine, un grazie a tutte le persone che ho incontrato durante i sei mesi trascorsi a Parigi. In particolare Bashar per la simpatia ed allegria (*je m'en fous de toi*) e Lorenzo per il suo continuo supporto tecnico e morale.

*Finally, thanks to all people I have met during six months in Paris. In particular Bashar for his pleasantness and hilarity (*je m'en fous de toi*) and Lorenzo for his continuous technical and moral support.*

Experimental and theoretical study on the
creep behavior of GFRP pultruded beams

Contents

I	Introduction	4
1	Fiber Reinforced Polymer (FRP) composites	6
1.1	Fibers	7
1.2	Matrix	8
1.3	Pultrusion	10
1.4	Durability	12
II	Mechanics of FRP Composites	14
2	Linear elastic behavior	16
2.1	Stress-strain relations	16
2.2	Engineering constants	21
2.2.1	Longitudinal modulus (E_1)	22
2.2.2	Transverse modulus (E_2)	23
2.2.3	Poisson modulus (ν_{12})	25
2.2.4	Shear modulus (G_{12})	26
3	Viscoelastic behavior	29
3.1	Theoretical approach	33
3.1.1	Maxwell model	33
3.1.2	Kelvin-Voigt model	34
3.1.3	Maxwell-Kelvin model	34
3.2	Empirical approach	36
3.2.1	Findley's model	36
3.2.2	Schapery's model	40
4	Material failure	45
4.1	Static strength	45
4.1.1	Tensile strength	45
4.1.2	Compressive strength	48
4.1.3	Failure criteria	52
4.1.3.1	Maximum stress failure criterion	52
4.1.3.2	Maximum strain failure criterion	53
4.1.3.3	Hoffman failure criterion	55
4.2	Creep failure	56
4.3	Fatigue strength	58

5	Influence of environmental factors	60
III	Structural Design of Pultruded Composite Elements	63
6	Theoretical approach	65
6.1	Euler-Bernoulli theory	66
6.2	Timoshenko theory	68
6.3	Findley's approach	70
7	Standards and codes	73
7.1	CUR96 Guidelines	73
7.2	Eurocomp Design Code	74
7.3	Guidelines of the Italian National Research Council	76
7.4	Bank's Compilation	77
IV	Experimental Activities	79
8	Literature review	81
8.1	Time-Temperature-Stress Superposition Principle	81
9	Applicability of the TTSSP for the characterization of the creep behavior of GFRP pultruded beams in the long term	87
9.1	Introduction	87
9.2	Experimental programme	88
9.3	Experimental setup	89
9.4	Materials	96
9.5	Results and discussion	97
9.5.1	Pure bending state	97
9.5.2	Shear-bending state	107
9.6	Conclusions	118
V	Theoretical Modelling	120
10	Literature review	122
10.1	Damage mechanics	122
10.2	Bifurcation theory	126
11	Development of a micromechanical model for UD composites	135
11.1	Formulation of the problem	135
11.2	Constitutive equations	136
11.2.1	Fibers	136
11.2.2	Matrix	141
11.2.2.1	Elastic	141
11.2.2.2	Plastic	141
11.2.2.3	Viscoelastic	146
11.3	Linear Stability Analysis (LSA)	147
11.3.1	Elastic matrix	148

11.3.1.1	Theoretical developments	148
11.3.1.2	Numerical examples and discussion	153
11.3.2	Plastic matrix	154
11.3.2.1	Theoretical developments	154
11.3.2.2	Numerical examples and discussion	156
11.3.3	Viscoelastic matrix	156
11.3.3.1	Theoretical developments	156
11.3.3.2	Numerical examples and discussion	159
11.4	Discussion and conclusions	160
VI	Conclusions	161
	Bibliography	164
	Annexes of Experimental Activities	168