

1989

Methodology for assessment of serviceability of aged transmission line conductors

Gary Francis Brennan
University of Wollongong

Follow this and additional works at: <https://ro.uow.edu.au/theses>

University of Wollongong

Copyright Warning

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site.

You are reminded of the following: This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author. Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material.

Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Recommended Citation

Brennan, Gary Francis, Methodology for assessment of serviceability of aged transmission line conductors, Master of Engineering (Hons.) thesis, Department of Mechanical Engineering, University of Wollongong, 1989. <https://ro.uow.edu.au/theses/2520>

NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

**METHODOLOGY FOR ASSESSMENT OF
SERVICEABILITY OF AGED
TRANSMISSION LINE CONDUCTORS**

A thesis submitted in fulfilment of the
requirements for the award of the degree

MASTER OF ENGINEERING (HONOURS)

from

THE UNIVERSITY OF WOLLONGONG

by

GARY FRANCIS BRENNAN B.E. (HONS)



DEPARTMENT OF MECHANICAL ENGINEERING

1989

I hereby declare that I have not submitted this material either in whole or in part, for a degree at this or any other institution. Whilst this thesis has been prepared with the proper care, the information, advice, opinion and recommendations contained herein are offered, I accept no responsibility for the use of the information in any particular application.

A handwritten signature in blue ink, appearing to read 'Gary Brennan', with a stylized, flowing script.

GARY BRENNAN

30 NOVEMBER, 1989

ABSTRACT

The degradation of transmission line conductors is attributed to annealing, fatigue, corrosion, creep and in the case of an ACSR construction, stress redistribution in the aluminium and steel wires. A methodology for monitoring and testing for the degradation mechanisms is presented. Simple life expectancy models presented, give confidence in the long term serviceability of conductors.

The methodology and life expectancy models developed are based on examining and testing conductor samples that are representative of various stages of each of the degradation mechanisms. The conductor samples were removed from in service transmission lines that had over twenty years service experience.

ACKNOWLEDGEMENTS

The author wishes to thank the Department of Mechanical Engineering, University of Wollongong, MM Metals and The Electricity Commission of NSW for initially providing the opportunity to research and develop the subject material, creating an environment and atmosphere in which it was a pleasure and privilege to work and the continued support by funding and providing the facilities to carry out the work.

The most sincere thanks are directed to Dr. A. Gouch, Mr. P. Flanagan, Dr. A. Basu, Dr. P. Arnold and Dr. W. Plumbridge for their continuous supervision and interest in the project. Their encouragement, guidance and endless patience during the course of the studies was greatly appreciated.

The author is indebted to Mr F. Van Eimeren for the preparation of all the conductor samples and assistance during the course of the work. An appreciation is extended to Mr J. Maliphant for the scanning electron micrographs.

Thanks are also due to my colleagues on the Australian Standards Committee EL/10/1 - Conductors, for their continued interest and encouragement.

I owe a debt of gratitude to Wendy Douglas, Debbie Annetts, Gary Harris and Harry Allen for the cheerful and patient way they carried out the typing and associated drafting for the thesis. A thank you is also extended to David Guille, for his support during the final stages of the preparation of the thesis.

And finally, I would like to take the opportunity to express my deep gratitude to my wife Cheryle, for her support, encouragement and forbearance during the period of these studies. A special thanks also goes to my daughter, Sarah-Ann, for her cheerful smiles during difficult times.

<u>TABLE OF CONTENTS</u>	PAGE
TITLE PAGE	i
STATEMENT OF SOURCE AND DISCLAIMER	ii
ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF ABBREVIATIONS	xiii
LIST OF TABLES	xiv
LIST OF FIGURES	xxiv
LIST OF PLATES	xxiv
LIST OF SYMBOLS	xxviii
INTRODUCTION	xxxvi

CHAPTER ONE REVIEW OF THE LITERATURE

1.1 INTRODUCTION	1
1.2 CONDUCTOR TENSION AND SAG PROPERTIES	
1.2.1 H.B. Dwight 1926	2
1.2.2 D.O. Ehrenburg 1934	3
1.2.3 C.O. Boyse and N.G. Simpson 1944	4
1.2.4 M. Landau 1951	5
1.2.5 C.A. Jordan 1952	6
1.2.6 B.M. Pickens 1959	8
1.2.7 P.F. Winkleman 1960	9
1.2.8 J. Barrien 1975	11
1.2.9 G.R. Boal 1977	12

1.2.10	J. Bradbury, G.F. Kuska and D.J. Tarr 1982	13
1.2.11	J.S. Barrett, S. Dutta and O. Nigol 1983	14
1.2.12	Future Developments	15
1.3	CONDUCTOR MECHANICAL PROPERTIES	
1.3.1	G.W. Stickley 1932	16
1.3.2	E. Fritz 1960	17
1.3.3	J.B. Roche and E. Dziedzic 1968	18
1.3.4	J.R. Harvey 1969	19
1.3.5	J.R. Harvey and R.E. Larson 1970	21
1.3.6	Y. Nakayama and T. Kojima 1970	22
1.3.7	J.R. Harvey 1972	23
1.3.8	J. Bradbury, P. Dey, G. Orawski and K.H. Pickup 1975	24
1.3.9	V.T. Morgan 1979	25
1.3.10	O. Nigol and J.S. Barrett 1981	27
1.3.11	J.S. Barrett, P. Ralston and O. Nigol 1982	28
1.3.12	Future Developments	30
1.4	CONDUCTOR CORROSION RESISTANCE PROPERTIES	
1.4.1	J.S. Forrest and J.M. Ward 1954	31
1.4.2	R.D. Carter (undated)	33
1.4.3	J.R. Booker 1986	35
1.4.4	B.J. Maddock, J.G. Allnutt, J.M. Ferguson, K.G. Lewis, D.A. Swift, P.W. Teare and M.J. Tunstall 1986	36
1.4.5	Future Developments	37
1.5	CONDUCTOR FATIGUE PROPERTIES	
1.5.1	J.C. Little, D.G. MacMullan and J.V. Majercak 1950	38
1.5.2	J.S. Tompkins, L.L. Merrill and B. L. Jones 1956	39

1.5.3	R.F. Steidel, Jr 1959	40
1.5.4	M.B. Elton, A.R. Hard and A.H. Shealy 1959	41
1.5.5	J.C. Poffenberger and R.L. Swart 1965	43
1.5.6	W.G. Fricke, Jr and C.B. Rawlins 1968	43
1.5.7	R. Claren and G. Diana 1969	44
1.5.8	R.A. Carter and D.G. Quick 1979	45
1.5.9	A.S. Richardson, Jr and F.S. Smith 1981	46
1.5.10	W. Philipps, W. Carlshem and W. Buckner (Prior 1985)	47
1.5.11	T.V. Gopalan 1985	50
1.5.12	W.F. Buckner, R. Holm and K.G. Papailiou 1986	51
1.5.13	Future Developments	52
 CHAPTER TWO CONDUCTOR TENSION		
2.1	INTRODUCTION	54
2.2	FUNDAMENTAL THEORY	56
2.2.1	Vertical Conductor Sag	58
2.2.2	Conductor Tension	63
2.2.2.1	Conductor Horizontal Tension	70
2.2.2.2	Average Conductor Tension	71
2.2.2.3	Conductor Span Length	72
2.2.2.4	Conductor Physical Parameters	78
2.2.2.5	Conductor Temperature	82
2.2.3	Sag Tension Evaluation by Strain Summation (STESS)	84
2.2.3.1	Thermal Strain	85
2.2.3.2	Slack	87
2.2.3.3	Elastic Strain	87
2.2.3.4	Creep Strain	87

2.2.3.5	Settling Strain	88
2.2.2.6	Other Features of STRESS	89
2.3	CONDUCTOR SAG MEASUREMENT THEORY	89
2.3.1	Tangent Observation Method	90
2.3.2	Satellite Observation Method	93
2.3.3	Conductor Temperature Measurement	97
2.3.4	Systematic Errors	98
2.4	TRANSMISSION LINE SAMPLES	103
2.5	CONDUCTOR SAG TENSION MEASUREMENTS	107
2.5.1	Summary of Results	107
2.5.2	Conductor Permanent Elongation	108
2.5.3	Conductor Clearance Margin	113
2.6	CONCLUSION	114
 CHAPTER THREE MECHANICAL PROPERTIES OF AGED CONDUCTORS		
3.1	INTRODUCTION	116
3.2	TRANSMISSION LINE CONDUCTOR SAMPLES	121
3.2.1	Conductor Removal	123
3.3	METALLOGRAPHIC EXAMINATION	126
3.3.1	Macroexamination	126
3.3.2	Microexamination	135

3.4	MECHANICAL TESTS	140
3.4.1	Wire Tests	140
3.4.1.1	Cross Section Area	146
3.4.1.2	Mechanical Properties	152
3.4.1.3	Electrical Properties	167
3.4.1.4	Steel Wire Galvanizing Properties	173
3.4.2	Conductor Tests	188
3.4.2.1	Stress Strain	190
3.4.2.2	Coefficient of Linear Expansion	208
3.4.2.3	Creep	217
3.4.2.4	Breaking Load	233
3.4.2.5	Lay Ratio	241
3.5	CHEMICAL TESTS	248
3.5.1	Material Composition	250
3.5.2	Grease/Tar Drop Point	253
3.5.3	Grease/Tar Mass	256
3.6	METHODOLOGY FOR TESTING AGED CONDUCTORS	257
3.6.1	Corrosion	259
3.6.2	Fatigue	261
3.6.3	Annealing	264
3.6.4	Creep	269
3.6.5	Electrical	269
3.6.6	Mechanical	271
3.6.7	Stress Distribution Degradation	272

3.7	CONCLUSION	273
3.7.1	Avon Kemps Creek Transmission Line	277
3.7.2	Dapto Springhill Transmission Line	279
3.7.3	Tomago Taree Transmission Line	280
3.7.4	Bellambi Heathcote Transmission Line	281
 CHAPTER 4 CONDUCTOR FATIGUE		
4.1	INTRODUCTION	282
4.2	FUNDAMENTAL VIBRATION THEORY	283
4.2.1	Aeolian Vibration	283
4.2.2	Wind Velocity Conductor Amplitude Relationship	287
4.2.3	Wind Velocity and Dynamic Stress Relationship	291
4.2.4	Conductor Displacement and Dynamic Stress Relationship	295
4.2.5	Conductor Static Load Stress	296
4.3	FATIGUE CHARACTERISTICS OF CONDUCTORS	297
4.3.1	Fatigue Properties of Aluminium	297
4.3.2	Conductor Fatigue Mechanism	299
4.3.3	Cumulative Damage Theory	303
4.4	FATIGUE TESTS	308
4.4.1	Test Apparatus	308
4.4.2	Instrumentation	313
	4.3.2.1 Wire Break Detection	313
	4.3.2.2 Conductor Amplitude Detection	315
	4.3.2.3 Conductor Frequency	317
	4.3.2.4 Data Logging	319

4.4.3	Test Program	319
4.4.4	Test Results	321
4.5	CONCLUSION	321
APPENDIX ONE REFERENCES		324
APPENDIX TWO SAG TENSION TEST RESULTS		332
A2.1	Survey and Calculated Datum	332
A2.1.1	Avon Kemps Creek Transmission Line	332
A2.1.2	Dapto Springhill Transmission Line	332
APPENDIX THREE AGED CONDUCTORS MECHANICAL PROPERTIES TEST RESULTS		340A
A3.1	METALLOGRAPHIC EXAMINATION	340A
A3.1.1	MACROEXAMINATION	340A
A3.1.1.1	Avon Kemps Creek Transmission Line	340A
A3.1.1.2	Dapto Springhill Transmission Line	342
A3.1.1.3	Tomago Taree Transmission Line	342
A3.1.1.4	Bellambi Heathcote Transmission Line	344
A3.1.2	MICROEXAMINATION	345
A3.2	WIRE TESTS	346
A3.2.1	Cross Section Area	346
A3.2.2	Mechanical Properties	346
A3.2.3	Electrical Properties	347
A3.2.4	Galvanized Steel Zinc Coating Mass	347
A3.2.5	Galvanized Steel Wire Wrap Tests	347
A3.3	CONDUCTOR TESTS	348
A3.3.1	Stress Strain	348
A3.3.2	Coefficient of Linear Expansion	349

A3.3.3	Creep	350
A3.3.4	Breaking Load	351
A3.3.5	Lay Lengths	351
A3.4	CHEMICAL TESTS	352
APPENDIX FOUR CONDUCTOR FATIGUE TEST RESULTS		428

LIST OF ABBREVIATIONS

AAAC	-	All Aluminium Alloy Conductor
AAC	-	All Aluminium Conductor
ACAR	-	Aluminium Conductor Aluminium (Alloy) Reinforced
ACSR	-	Aluminium Conductor Steel Reinforced
CBL	-	Calculated Breaking Load
CONCAT	-	Continuous Catenary
CLE	-	Coefficient of Linear Expansion
EDT	-	Every Day Tension
GZ	-	Galvanized Zinc
MWT	-	Maximum Working Tension
MOT	-	Maximum Operating Temperature
NDT	-	Non Destructive Testing
SEM	-	Scanning Electron Microscopy
STESS	-	Sag Tension by Strain Summation
UTS	-	Ultimate Tensile Strength

LIST OF TABLES

	Page
2.1 Conductor Ground Clearance for Open Country	59
2.3 Transmission Line Sample Data	104
2.4 Physical Characteristics of Moose Conductor	106
2.5 Avon to Kemps Creek Transmission Line Summary of Sag & Tension Measurements & Calculations	107
2.6 Dapto to Springhill Transmission Line Summary of Sag & Tension Measurements & Calculations	108
2.7 Conductor Permanent Elongation Results	110
3.1 IEC Recommendation Pollution Severity Levels	122
3.2 Summary of Aluminium Wire Test Results Cross Sectional Area	149
3.3 Summary of Steel Wire Test Results Cross Sectional Area	150
3.4 Summary of Aluminium Wire Test Results Breaking Load	157
3.5 Summary of Steel Wire Test Results Breaking Load	158
3.6 Summary of Aluminium Wire Test Results UTS	159
3.7 Summary of Steel Wire Test Results UTS	160
3.8 Summary of Aluminium Wire Test Results Elongation	161
3.9 Summary of Steel Wire Test Results Elongation	162
3.10 Summary of Aluminium Wire Test Results Resistivity	172
3.11 Summary of Conductor Test Results Modulus of Elasticity	206
3.12 Summary of Conductor Test Results Stress Strain	207
3.13 Summary of Conductor Test Results Coefficient of Linear Expansion	216
3.14 Aluminium and Aluminium Alloy Melting Temperatures	220
3.15 Summary of Conductor Test Results Breaking Load	239
3.16 Polynomial Modelling of Breaking Load Tests Table of Coefficients	244

LIST OF TABLES (CONT)

	Page
3.17 Summary of Conductor Test Results Lay Ratio	249
3.18 Chemical Composite Limits of Aluminium and Aluminium Alloys	251
3.19 Summary of Chemical Test Results, Corrosion Protection Material Drop Point and Mass and Maximum Design Operating Temperature	255
3.20 Typical Grease Mass in Conductors	258
4.1 Transmission Line Conductor Flexural Rigidity	294
4.2 Summary of Fatigue Test Results Nepture 19/3.25 mm AAC	321
A3.1 Cross sectional area Avon to Kemps Creek TL	368
A3.2 Cross sectional area Dapto to Springhill TL	369
A3.3 Cross sectional area Tomago to Taree TL	370
A3.4 Cross sectional area Bellambi to Heathcote TL	371
A3.5 Mechanical Properties Avon to Kemps Creek TL	372
A3.6 Mechanical Properties Dapto to Springhill TL	373
A3.7 Mechanical Properties Tomago to Taree TL	374
A3.8 Mechanical Properties Bellambi to Heathcote TL	375
A3.9 Electrical Properties Avon to Kemps Creek TL	376
A3.10 Electrical Properties Dapto to Springhill TL	377
A3.11 Electrical Properties Tomago to Taree TL	378
A3.12 Electrical Properties Bellambi to Heathcote TL	379
A3.13 Zinc Coating Mass Avon to Kemps Creek TL	380
A3.14 Zinc Coating Mass Dapto to Springhill TL	380
A3.15 Zinc Coating Mass Tomago to Taree TL	381

LIST OF TABLES (CONT)

	Page
A3.16 Zinc Coating Mass Bellambi to Heathcote TL	381
A3.17 Stress Strain Test No. 52 Test Result Data Tomago to Taree TL	385
A3.18 Stress Strain Test No. 53 Test Result Data Tomago to Taree TL	389
A3.19 Stress Strain Test No. 61 Test Result Data Dapto to Springhill TL	393
A3.20 Stress Strain Test No. 62 Test Result Data Avon to Kemps Creek TL	397
A3.21 Coefficient of Linear Expansion Test No. 43 Test Result Data Tomago to Taree TL	399
A3.22 Coefficient of Linear Expansion Test No. 44 Test Result Data Tomago to Taree TL	401
A3.23 Coefficient of Linear Expansion Test No. 50 Test Result Data Dapto to Springhill TL	403
A3.24 Coefficient of Linear Expansion Test No. 52 Test Result Data Avon to Kemps Creek TL	405
A3.25 Conductor Creep Test Result Data Avon to Kemps Creek TL	408
A3.26 Conductor Creep Test Result Data Dapto to Springhill TL	411
A3.27 Breaking Load Test No. 163 Test Result Data Tomago to Taree TL	414
A3.28 Breaking Load Test No. 164 Test Result Data Tomago to Taree TL	416
A3.29 Breaking Load Test No. 205 Test Result Data Avon to Kemps Creek TL	418

LIST OF TABLES (CONT)

	Page
A3.30 Breaking Load Test No. 206 Test Result Data Avon to Kemps Creek TL	420
A3.31 Breaking Load Test No. 207 Test Result Data Dapto to Springhill TL	422
A3.32 Breaking Load Test No. 208 Test Result Data Dapto to Springhill TL	424
A3.33 Lay Length Dapto to Springhill TL	425
A3.34 Lay Length Avon to Kemps Creek TL	425
A3.35 Chemical Test Test Result Data Tomago to Taree TL	426
A3.36 Chemical Test Test Result Data Bellambi to Heathcote TL	426
A3.37 Chemical Test Test Result Data Avon to Kemps Creek TL	427
A3.38 Chemical Test Test Result Data Dapto to Springhill TL	427
 A4.1 Conductor Fatigue Test Data Test No. NEP/1	 429
A4.2 Conductor Fatigue Test Log Test No. NEP/1	430
A4.3 Conductor Fatigue Test Data Test No. NEP/2	432
A4.4 Conductor Fatigue Test Log Test No. NEP/2	433
A4.5 Conductor Fatigue Test Data Test No. NEP/3	435
A4.6 Conductor Fatigue Test Log Test No. NEP/3	437
A4.7 Conductor Fatigue Test Data Test No. NEP/4	439
A4.8 Conductor Fatigue Test Log Test No. NEP/4 Sheet 1	441
A4.9 Conductor Fatigue Test Log Test No. NEP/4 Sheet 2	442
A4.10 Conductor Fatigue Test Data Test No. NEP/5	444
A4.11 Conductor Fatigue Test Log Test No. NEP/5	446
A4.12 Conductor Fatigue Test Data Test No. NEP/6	448
A4.13 Conductor Fatigue Test Log Test No. NEP/6	450

LIST OF FIGURES

	Page
2.1 Catenary and Parabolic Sag Equations Level Spans	60
2.2 Catenary and Parabolic Sag Equations Non Level Spans	61
2.3 Parabolic Sag Error	62
2.4 Parabolic Conductor Length Error	64
2.5 Catenary Change of State Equation	68
2.6 Parabolic Change of State Equation	69
2.7 Catenary/Span Length Error	74
2.8 Conductor Tension & Sag Change with Change in Mass	80
2.9 Conductor Tension & Sag Change with Change in CSA or Modulus of Elasticity	80
2.10 Conductor Tension & Sag Change with Change in CLE	81
2.11 Conductor Tension & Sag Change with Change in Ultimate Tensile Strength	81
2.12 Expansion of Aluminium Component of an ACSR/GZ Conductor	86
2.13 Transformed Ordinate and Abscissa Axis of Catenary Curve	92
2.14 Parabolic Span Least Squares Method of Analysis	95
2.15 Calibration Curve of Live Line Temperature Measuring Equipment	100
2.17 Stringing Chart for Moose ACSR Conductor	105
3.1 Relationship of Service Conditions and Conductor Degradation Mechanism	120
3.2 Distribution of Diameter of 3.00 mm 1350 Wire	142
3.3 Distribution of UTS of 3.00 mm 1350 Wire	143
3.4 Distribution of Resistivity of 3.00 mm 1350 Wire	144
3.5 Percentage of Original Tensile Strength for Alloy 1350 Vs Aging Time	153

LIST OF FIGURES (CONT)

	Page
3.6 Percentage of Original Tensile Strength for Alloy 1120 Vs Aging Time	154
3.7 Percentage of Original Tensile Strength for Alloy 6201 Vs Aging Time	155
3.8 Electrical Conductivity for Alloy 1350 Vs Time and Temperature	168
3.9 Electrical Conductivity for Alloy 1120 Vs Time and Temperature	169
3.10 Electrical Conductivity for Alloy 6201 Vs Time and Temperature	170
3.12 Degradation of Galvanising Coating for ACSR/GZ Conductor	176
3.13 Degradation of Galvanising Coating for 30/7/3.00	177
3.14 Degradation of Galvanising Mass 3.00 mm Wire	179
3.15 30/7/2.50 mm ACSR/GZ/1120 Stress Strain Test Results Raw Data Plot Composite	192
3.16 30/7/2.50 mm ACSR/GZ/1120 Stress Strain Test Results Raw Data Plot Core	193
3.17 30/7/2.50 mm ACSR/GZ/1120 Stress Strain Test Results Zero Corrected Plot Composite	195
3.18 30/7/2.50 mm ACSR/GZ/1120 Stress Strain Test Results Zero Corrected Plot Core	196
3.19 30/7/2.50 mm ACSR/GZ/1120 Stress Strain Test Results Master Stress Strain Curves	197
3.20 54/6/3.53 + 1/3.71 ACSR/GZ Transition Tension and Conductor Tension Change with Change in Temperature	204
3.21 7/4.75 mm AAC Coefficient of Linear Expansion Test Results Raw Data and Linear Regression Plot	211
3.22 Wire Geometry in a Helically Stranded Conductor	213
3.23 Low and High Temperature Creep	218
3.24 7/4.75 mm AAC Conductor Creep Test Results Linear Linear Plot	224

LIST OF FIGURES (CONT)

	Page
3.25 7/4.75 mm AAC Conductor Creep Test Results Log Log Plot	225
3.26 7/4.75 mm AAC Conductor Creep Rate	227
3.27 7/4.75 mm AAC Conductor Tension and Sag Change with Change in Time	229
3.29 Summary of Conductor Test Results Creep	232
3.30 Conductor Tension & Sag Change with Change in Time 54/6/3.53 + 1/3.71 mm ACSR/GZ with Preformed Steel Core Wires	234
3.31 Conductor Tension & Sag Change with Change in Time 54/6/3.53 + 1/3.71 mm ACSR/GZ with No Preformed Steel Core Wires	235
3.32 Polynomial Modelling of Breaking Load Tests Panther ACSR/GZ 30/7/2.99 mm Conductor	242
3.33 Polynomial Modelling of Breaking Load Tests Moose ACSR/GZ 54/7/3.53 mm + 1/3.71 mm Conductor	243
3.34 Wire Geometry in a Helically Stranded Conductor	245
3.35 Methodology for Testing Steel Wires in Aged Conductors	262
3.36 Methodology for Testing Fatigue of Aluminium Wires in Aged Conductors	270 265
3.37 Methodology for Testing of Aged Conductors, Annealing of Aluminium Wires	268
3.38 Methodology for Testing Creep in Aged Conductors	
3.39 Methodology for Testing Stress Distribution Changes in Aged Conductors	274
3.40 Summary of Degradation Mechanisms and Assessment Procedures for Aged Conductors	278
4.1 Relationship of Vibration Frequency to Conductor Diameter	286

LIST OF FIGURES (CONT)

	Page
4.2 Relationship of Conductor Parameters to Conductor Vibration Loop Length	288
4.3 Predicted Conductor Vibration and Amplitude	289
4.4 Diana Frequency and Amplitude Predication	290
4.5 Relationship of Conductor Deflection to Conductor Diameter	292
4.6 Fatigue Curves Separate Wires and Stranded Conductors	305
4.7 Miners Cumulative Damage Theory	307
4.8 Conductor Rotating Torque	314
4.10 Conductor Fatigue Test Program	320
4.11 S-N Fatigue Curve 19/3.25 mm AAC Conductor	322
A2.1 Avon to Kemps Creek TL Profile Structures 51 to 52	333
A2.2 Avon to Kemps Creek TL Profile Structures 52 to 53	334
A2.3 Avon to Kemps Creek TL Profile Structures 53 to 54	335
A2.4 Dapto to Springhill TL Profile Structures 317A to 318A	336
A2.5 Dapto to Springhill TL Profile Structures 318A to 319A	337
A2.6 Dapto to Springhill TL Profile Structures 319A to 320A	338
A2.7 Dapto to Springhill TL Profile Structures 320A to 321A	339
A2.8 Dapto to Springhill TL Profile Structures 321A to 322A	340
A3.1 Stress Strain Test Raw Plot of Test Data Composite Tomago to Taree TL	382
A3.2 Stress Strain Test Raw Plot of Test Result Data Core Tomago to Taree TL	383
A3.3 Stress Strain Test Derived Test Results Tomago to Taree TL	384

LIST OF FIGURES (CONT)

	Page
A3.4 Stress Strain Test Raw Plot of Test Results Data Composite Tomago to Taree TL	386
A3.5 Stress Strain Test Raw Plot of Test Results Data Core Tomago to Taree TL	387
A3.6 Stress Strain Test Derived Test Result Tomago to Taree TL	388
A3.7 Stress Strain Test Raw Plot of Test Results Data Composite Dapto to Springhill TL	390
A3.8 Stress Strain Test Raw Plot of Test Result Data Core Dapto to Springhill TL	391
A3.9 Stress Strain Test Derived Test Result Dapto to Springhill	392
A3.10 Stress Strain Test Raw Plot of Test Result Data Commposite Avon to Kemps Creek TL	394
A3.11 Stress Strain Test Raw Plot of Test Result Data Core Avon to Kemps Creek TL	395
A3.12 Stress Strain Test Derived Test Result Avon to Kemps Creek TL	396
A3.13 CLE Test Raw Plot and Linear Regression Test Results Tomago to Taree TL	398
A3.14 CLE Test Raw Plot and Linear Regression Test Results Tomago to Taree TL	400
A3.15 CLE Test Raw Plot and Linear Regression Test Results Dapto to Springhill TL	402
A3.16 CLE Test Raw Plot and Linear Regression Test Results Avon to Kemps Creek TL	404
A3.17 Creep Test Raw Test Result Avon to Kemps Creek TL	406
A3.18 Creep Test Raw Test Result Avon to Kemps Creek TL	407
A3.19 Creep Test Raw Test Result Dapto to Springhill TL	409
A3.20 Creep Test Raw Test Result Dapto to Springhill TL	410

LIST OF FIGURES (CONT)

	Page
A3.21 Conductor Creep Test Temperature Variation	412
A3.22 Composite Conductor Breaking Load Test No. 163	413
A3.23 Composite Conductor Breaking Load Test No. 164	415
A3.24 Composite Conductor Breaking Load Test No. 205	417
A3.25 Composite Conductor Breaking Load Test No. 206	419
A3.26 Composite Conductor Breaking Load Test No. 207	421
A3.27 Composite Conductor Breaking Load Test No. 208	423
 A4.1 Conductor Fatigue Test Test Results Test No. NEP/1	 431
A4.2 Conductor Fatigue Test Test Results Test No. NEP/2	434
A4.3 Conductor Fatigue Test Spectrum Analysis Test No. NEP/3	436
A4.4 Conductor Fatigue Test Test Results Test No. NEP/4	438
A4.5 Conductor Fatigue Test Spectrum Analysis Test No. NEP/4	440
A4.6 Conductor Fatigue Test Test Results Test No. NEP/4	443
A4.7 Conductor Fatigue Test Test Spectrum Analysis No. NEP/5	445
A4.8 Conductor Fatigue Test Test Results Test No. NEP/5	447
A4.9 Conductor Fatigue Test Spectrum Analysis Test No. NEP/6	449
A4.10 Conductor Fatigue Test Test Results Test No. NEP/6	451

LIST OF PLATES

	Page
2.1 Accumulation of Ice and Snow on Transmission Line Conductors	66
2.2 Direct Line Conductor Temperature Measuring Instruments	99
2.3 Application of Conductor Temperature Measuring Instruments	101
3.1 Fitting of Bonding Tape to the Conductor Sample	124
3.2 Fitting of Wooden Cleats to the Conductor Sample	125
3.3 19/3.25 AAC Conductor, Conductor Fretting and Fatigue Crack	129
3.4 7/4.22 AAAC/6201 Conductor, Broken Strand Adjacent Suspension Clamp	129
3.5 30/7/3.00 mm ACSR/GZ Conductor, 18 Wire Layer Surface pitting Magnification x 200	132
3.6 SEM of 19/3.25 mm AAC, Aluminium Wire Fatigue Crack Surface	137
3.7 SEM of 19/3.25 mm AAC, Longitudinal Section of Fatigue Crack	137
3.8 SEM of 30/7/2.36 mm ACSR/GZ, Longitudinal Section of Galvanizing Coating of Steel Wire	138
3.9 SEM of 19/3.75 mm AAC, 12 Wire Layer Fatigue Fretting Magnification x 200	147
3.10 SEM of 30/7/2.997 mm ACSR/GZ, 6 Wire Layer Steel Strand Loss of Galvanizing Magnification x 200	148
3.11 SEM of 30/7/2.997 mm ACSR/GZ 6 Wire Layer Steel Strands Poor Zinc Adhesion	175
3.12 7/2.99 mm Tarred and Aged GZ Wire After 408 Hours Salt Spray Exposure As Found Sample	180
3.13 7/3.00 mm New and Greased Wire After 864 Hours Salt Spray Exposure As Found Sample	180
3.14 30/7/2.99 mm ACSR/GZ 18 Wire Layer Aged and Tarred Sample after 864 Hours Salt Spray Exposure	182

LIST OF PLATES (CONT)

	Page
3.15 30/7/3.00 mm ACSR/GZ 18 Wire Layer New and Greased Sample after 864 Hours Salt Spray Exposure	182
3.16 30/7/2.99 mm ACSR/GZ 6 Wire Layer Aged and Tarred Sample after 864 Hours Salt Spray Exposure	183
3.17 30/7/3.00 mm ACSR/GZ 6 Wire Layer New and Greased Sample after 864 Hours Salt Spray Exposure	183
3.18 30/7/2.99 mm ACSR/GZ 6 Wire Layer Aged and Tarred Sample after 864 Hours Salt Spray Exposure Localised Brown Staining	184
3.19 30/7/3.00 mm ACSR/GZ 6 Wire Layer New and Greased Sample after 864 Hours Salt Spray Exposure Localised Discolouration of Zinc Coating	184
3.20 30/7/2.99 mm ACSR/GZ 6 Wire Layer Aged and Tarred Sample after 864 Hours Salt Spray Exposure Cross Section Showing Localised Loss of Zinc Coating	185
3.21 30/7/3.00 mm ACSR/GZ 6 Wire Layer Aged and Tarred Sample after 864 Hours Salt Spray Exposure Cross Section Showing Localised Loss of Zinc Coating	185
3.22 Section of Epoxy/Compression Termination of an ACSR Construction	240
3.23 Section of Epoxy/Compression Termination of an ACSR Construction Showing Compression Sleeve	240
4.1 Fretting Fatigue 19/3.25 mm AAC Construction	302
4.2 Fatigue Failure 19/3.25 mm AAC Construction	304
4.3 General Arrangement of Conductor Fatigue Tester	309
4.4 Conductor Termination Block and Static Stress Strain Gauge Arrangement	311
4.5 Conductor Fatigue Tester Conductor Mechanical Actuator	312
4.6 Conductor Fatigue Tester Wire Break Detection Arrangement	316
4.7 Conductor Fatigue V-Scope Measurement Technique	318

LIST OF PLATES (CONT)

	Page
A3.1 Avon to Kemps Creek TL 24 Wire A1 Layer or Outside Layer	353
A3.2 Avon to Kemps Creek TL 18 Wire A1 Layer	353
A3.3 Avon to Kemps Creek TL 12 Wire A1 Layer	354
A3.4 Avon to Kemps Creek TL 6 Wire Steel Layer	354
A3.5 Avon to Kemps Creek TL Steel Layer	355
A3.6 Dapto to Springhill TL 24 Wire A1 Layer or Outside Layer	356
A3.7 Dapto to Springhill TL 18 Wire A1 Layer	356
A3.8 Dapto to Springhill TL 12 Wire A1 Layer	357
A3.9 Dapto to Springhill TL 6 Wire Steel Layer Without Preform	357
A3.10 Dapto to Springhill TL Steel Core	358
A3.11 Tomago to Taree TL 18 Wire Layer or Outside Layer After Destranding Armour Rods	359
A3.12 Tomago to Taree TL 18 Wire A1 Layer or Outside Layer	359
A3.13 Tomago to Taree TL 12 Wire A1 Layer and Underside of 18 Wire A1 Layer	360
A3.14 Tomago to Taree TL 6 Wire Steel Layer and Underside of 12 Wire A1 Layer	360
A3.15 Tomago to Taree TL Destranded 6 Wire Steel Layer and Steel Core	361
A3.16 Tomago to Taree TL Destranded and Cleaned 6 Wire Steel Layer and Steel Core	361
A3.17 Bellambi to Heathcote TL 12 Wire A1 Layer or Outside Layer	362
A3.18 Bellambi to Heathcote TL 12 Wire A1 Layer and Underside of 18 Wire Layer	362
A3.19 Bellambi to Heathcote TL 6 Wire Layer and Underside of the 12 Wire Layer	363

LIST OF PLATES (CONT)

	Page
A3.20 Bellambi to Heathcote TL Destrand 6 Wire Steel Layer and Steel Core	363
A3.21 Bellambi to Heathcote TL Destrand and Cleaned 6 Wire Steel Layer and Steel Core	364
A3.22 Typical Elliptical Area Damage of Aluminium Strands	365
A3.23 Longitudinal Section of Elliptical Area Damage of Aluminium Strands x 100	365
A3.24 Longitudinal Section of Typical Outer Aluminium Layer Pitting x 200	366
A3.25 Longitudinal Section of 18 Wire Layer Aluminium Pitting from Tomago to Taree TL x 50	366
A3.26 Loss of Galvanizing from Steel Core from Tomago to Taree TL x 200	367
A3.37 Corrosion of Steel Wire from 6 Wire Layer from Tomago to Taree x 100	367

LIST OF SYMBOLS

The symbols used in this thesis are, as far as possible, the symbols in common use by the electrical industry and published works. In some cases, as a result of the diverse nature of the thesis, the symbols may define more than one parameter. In this regard, to assist the reader, the symbols used, have been categorised into chapters. However in achieving a consistent approach, some duplication in the list of symbols from one chapter to the next will occur.

CHAPTER ONE

E_a	-	modulus of elasticity of aluminium in Pa
E_s	-	modulus of elasticity of steel in Pa
m	-	ratio of cross section area of steel to the total conductor
n	-	ratio of cross section area of aluminium to the total conductor
z	-	parameter
ϵ	-	parameter
α_a	-	aluminium CLE in $^{\circ}\text{C}^{-1}$
α_s	-	steel CLE in $^{\circ}\text{C}^{-1}$

CHAPTER TWO

A	-	conductor cross sectional area in m^2
A_2	-	conductor creep constant
C	-	constant
c	-	conductor curve constant
D_a	-	aluminium thermal strain in mm.km^{-1}
D_s	-	steel thermal strain in mm.km^{-1}

LIST OF SYMBOLS (CONT)

E	-	conductor modulus of elasticity in Pa
H	-	vertical distance between two adjacent conductor attachment points in m
K_r	-	conductor radial thermal conductivity coefficient in $W.m^{-1}.C$
L	-	horizontal span distance in m
l	-	conductor chord length in m
L_{eff}	-	effective level span length for a non level span
L_E	-	equivalent span in m
n_1, n_2	-	conductor creep constants
R	-	d.c. resistance of conductor in $\Omega.m^{-1}$
r_c	-	radius of conductor in m
r_s	-	radius of steel core of an ACSR conductor in m
S	-	conductor sag in m
s	-	conductor stress in Pa
T	-	conductor tension in N
T_h	-	conductor horizontal tension in N
T_{AV}	-	conductor average tension in a span in N
t	-	time in hours
t'	-	conductor tension at any point in the chord length in N
\times	-	conductor weight load in N
ω	-	conductor weight load in N
α	-	conductor CLE in $^{\circ}C^{-1}$

LIST OF SYMBOLS (CONT)

θ	-	conductor temperature in $^{\circ}\text{C}$
θ_c	-	conductor core temperature in $^{\circ}\text{C}$
θ_s	-	conductor surface temperature in $^{\circ}\text{C}$
θ_a	-	aluminium temperature in $^{\circ}\text{C}$
θ_s'	-	steel temperature in $^{\circ}\text{C}$
$\mu\epsilon$	-	conductor creep in mm.km^{-1}
δ	-	conductor creep constant
γ	-	an angle in degrees

CHAPTER THREE

A_2	-	conductor creep constant
A_a	-	aluminium cross sectional area in m^2
A_c	-	conductor cross sectional area in m^2
A_{ci}	-	wire area constant for the i th layer
A_n	-	polynomial constant, where $n = 1, 2, 3 \dots \text{etc.}$
A_s	-	steel cross sectional area in m^2
B_n	-	polynomial constant, where $n = 1, 2, 3 \dots \text{etc.}$
BL_s	-	steel wire breaking load in N
BL_{ij}	-	breaking load of the i th wire of material j
C_a	-	aluminium permanent elongation in m.m^{-1} in a stress strain test
C_s	-	steel permanent elongation in m.m^{-1} in a stress strain test
E_a	-	modulus of elasticity of aluminium in Pa

LIST OF SYMBOLS (CONT)

E_{af}	-	final modulus of elasticity of aluminium in Pa
E_{cf}	-	final modulus of elasticity of conductor in Pa
E_{ci}	-	initial modulus of elasticity of conductor in Pa
E_s	-	modulus of elasticity of steel in Pa
E_{sf}	-	final modulus of elasticity of conductor in Pa
E_{si}	-	initial modulus of elasticity of conductor in Pa
E_w	-	modulus of elasticity of wire in Pa
E_x	-	wire axial modulus of elasticity in Pa
D	-	conductor diameter in m
F	-	conductor axial force in N
i	-	layer number
j	-	material type
L	-	wire length corresponding to one lay length in m
L_c	-	length of the centre wire from the conductor sample in m
LR	-	lay ratio
$Load$	-	instantaneous load in kN during a breaking load test
m	-	ratio of cross section area of steel to the total conductor
M_{ci}	-	wire mass constant for the i th layer
M_c	-	mass of conductor sample in $g.m^{-1}$
M_g	-	mass of grease or tar in g
M_z	-	mass of zinc in $g.m^{-1}$
MLR	-	mean lay ratio
n	-	ratio of cross section of aluminium to the total conductor

LIST OF SYMBOLS (CONT)

N_n	-	conductor creep constants where $n = 1, 2$ or 3
N_{ij}	-	number of wires in i layer of material j
N_i	-	number of wires in a conductor
R	-	conductor layer radius in m
R_{ci}	-	wire resistance constant for the i th layer
S	-	conductor stress in Pa
S_a	-	aluminium stress in Pa
S_{ao}	-	maximum aluminium stress in Pa at initial temperature
S_{av}	-	conductor average stress in Pa
S_b	-	conductor birdcaging stress in Pa
S_c	-	conductor stress in Pa
S_{co}	-	maximum conductor stress in Pa at initial temperature
S_{kt}	-	conductor critical stress in Pa
S_s	-	steel stress in Pa
S_{so}	-	maximum steel stress in Pa at initial temperature
T	-	temperature in $^{\circ}C$
t	-	time in hours
W_i	-	mass of the i th wire in g after destrandng of the conductor sample and removal of all grease or tar from the i th wire
ϵ	-	conductor strain in $m.m^{-1}$
ϵ_L	-	wire strain in $m.m^{-1}$
$\mu\epsilon$	-	conductor creep in $mm.km^{-1}$
λ	-	lay length in m
σ	-	lay angle in degrees

LIST OF SYMBOLS (CONT)

α	-	CLE in $^{\circ}\text{C}^{-1}$
α_a	-	aluminium CLE in $^{\circ}\text{C}^{-1}$
α_s	-	steel CLE in $^{\circ}\text{C}^{-1}$
α'	-	wire CLE in $^{\circ}\text{C}^{-1}$
α_c	-	conductor temperature in $^{\circ}\text{C}$
α_{cmax}	-	conductor maximum operating temperature in $^{\circ}\text{C}$
α_{dp}	-	grease/tar drop point in $^{\circ}\text{C}$
ϵ_L	-	wire strain in m.m^{-1}

CHAPTER 4

A	-	defined distance of 89 mm or 3-1/2 inches
A_a	-	aluminium cross sectional area in m^2
A_c	-	conductor cross sectional area in m^2
$a_{(i \text{ or } j)}$	-	area of the wires in the left hand lay layer (i) or the right hand lay layer (j)
a_c	-	homogenous conductor area in m
c	-	distance from the neutral plane to the outermost fibre in m
d_a	-	aluminium wire diameter in m
d_c	-	conductor diameter in m
d_s	-	steel wire diameter in m
d_{ij}	-	diameter of the wire in the ith layer of material j
d_w	-	wire diameter in m
E_a	-	modulus of elasticity of aluminium in Pa
E_j	-	modulus of elasticity of material j

LIST OF SYMBOLS (CONT)

E_s	- modulus of elasticity of steel in Pa
EI	- conductor flexural rigidity in $N.m^2$
f	- conductor vibration frequency in Hz
L	- conductor loop length in m
M	- wire torque in $N.m$
m	- conductor mass in g
m_{ij}	- number of wires in the i th layer of material j
N_i	- number of wires in a conductor
N_n	- fatigue life of material at a given stress level in cycles where $n = 1, 2, 3, \dots$ etc
$N_{(i \text{ or } j)}$	- number of wires in the left hand lay layer i or the right hand lay layer j
n	- ratio of cross section of aluminium to the total conductor
n_a	- number of aluminium wires
n_n	- proportion of material life at a given stress level in cycles where $n = 1, 2, 3, \dots$ etc
n_s	- number of steel wires
R	- bending radius of conductor over suspension point in m
r	- conductor layer radius in m
r_{ij}	- radius of the i th layer of material j
$r_{(i \text{ or } j)}$	- radius of the left hand layer i of the right hand layer j
S	- Strouhal number
T	- conductor tension in N
T_4	- conductor force producing rotating torque in N
v	- wind velocity in $m.s^{-1}$
Y	- conductor peak to peak displacement in mm
Y'	- conductor peak displacement in mm

LIST OF SYMBOLS (CONT)

y_a	- conductor deflection in m
σ	- conductor stress in Pa
σ_a	- aluminium wire stringing stress in Pa
σ_b	- conductor bending stress in Pa
σ_d'	- conductor stress at 89mm from the suspension point in Pa
$\sigma_{(i \text{ or } j)}$	- wire stress in the left hand lay layer i or the right lay layer j
θ	- lay angle in degrees
$\theta_{(i \text{ or } j)}$	- lay angle in the left hand lay layer i or the right hand lay layer j

INTRODUCTION

The transmission of power in New South Wales is achieved by over 70,000 km of steel reinforced aluminium conductors of varying size. The major part of these conductors were manufactured and erected between 1955 and 1970 making some of these conductors over 30 years old.

With time, the conductors have experienced a variety of in service conditions that may have varied from emergency operating conditions creating elevated temperatures to long exposures of low velocity winds inducing aeolian vibration. In addition, the pollution levels in the NSW transmission system range from light to very heavy.

The objective of these studies was to ascertain the level of degradation of the conductors, the continued serviceability of the conductors and develop a methodology to test conductors in the future. At the same time, a simple conductor life expectancy model was developed. The methodology presented, is based on actual conductor samples, having been exposed to pollution environments ranging from light to heavy, removed from service for testing. Testing and examinations for degradation of the removed conductor samples cover metallurgical examinations, wire tests and full scale conductor tests. The degradation mechanisms discussed include corrosion, fatigue, creep and annealing. Stress distribution changes in an ACSR construction is also discussed.

To assess the level of degradation of an aged conductor, the initial parameters of the conductor need to be established. Much of the discussions are devoted to establishing these initial properties of a conductor. This provides an understanding of the fundamentals of the conductor parameters and gives a greater appreciation as to the effects and consequences of conductor property changes.

In developing the methodology to assess in service conductor creep, a review of the various methods of determining conductor sag and tension was carried out. In addition, to gain a greater understanding of the fatigue mechanism of a conductor, a conductor fatigue tester was designed and constructed. Some S-N fatigue data for a AAC construction is given.

Initially a comprehensive review and appraisal of the available literature on the subject matter is presented.