CONTENTS

DEC	LARA	ΓΙΟΝ	i
APPI	ROVAI	L OF THE VIVA-VOCE BOARD	ii
CER'	TIFIC	ATE	iii
ACK	NOWI	LEDGEMENT	iv
ABS	FRAC		v
DDFI			vi
	TENT		VI
			viii
NOM	IENCL		XIV
ABB	REVIA	ATIONS	xvi
1	Intro	duction	1
-			-
	1.1	Introduction	1
	1.2	FRP composites: Constituents and characteristics	2
	1.3	Functionally Graded Materials (FGM): Constituents and characteristics	4
		1.3.1 Advantages and applications of the FGMs	5
		1.3.2 Manufacturing aspects of the FGMs	6
		1.3.3 Material property gradation schemes for the FGMs	7
	1.4	Joining of laminated FRP composites	8
		1.4.1 Bonded joint constituents	9
		1.4.1.1 Adhesive	10
	15	Adhesiye honded joint design philosophy	10
	1.5	1.5.1 Stress analyses	12
		1.5.2 Adhesion failure and delamination damage analyses	13
	1.6	Joining methods used in composite piping systems	15
	1.7	Scope of adhesion failure and delamination damage analyses of	
		bonded tubular joints made with laminated FRP composites and FGMs	16
2	Dari		10
4	Kevi	ew of Literature	19
	2.1	Introduction	19
	2.2	Damage classification of bonded joints	20
	2.3	Stress and failure analyses of adhesive bonded flat joints	21
		2.3.1 Stress analyses	21
		2.3.2 Delamination damage analyses	23
	2.4	Stress and failure analyses of adhesive bonded tubular joints	24
		2.4.1 Stress analyses	24
	-	2.4.2 Delamination damage analyses	25
	2.5	Stress and failure analyses of Functionally Graded Materials (FGMs)	26

	2.4	5.1 Stress analyses	27
	2.4	5.2 Failure analyses	29
	2.6 SE	RR: A fracture mechanics based parameter for characterizing	
	the	e growth of adhesion failures and delamination damages in	
	ad	hesive bonded joints	30
	2.7 Oł	ojectives of the present Thesis	31
3	Finite Ele	ement Modelling of Adhesion Failure and Delamination	
-	Damage A	Analyses of Bonded Tubular Joints	35
	3.1 Int	troduction	35
	3.2 Co	onstitutive relationship of laminated FRP composites	35
	3.3 Co	onstitutive elastic formulations for laminated FRP composites	41
	3.4 Th	ree-dimensional finite element formulations	44
	3.5 So	lution procedure	52
	3.6 Fi	nite element modelling of bonded tubular joints	53
	3.0	5.1 Isoparametric solid brick element (SOLID 45)	53
	3.0	5.2 Layered volume element (SOLID 46)	54
	3.0	5.3 Multi-Point Constraint element (MPC 184)	57
	3.0	5.4 Contact or gap element (CONTA 178)	57
	3.7 M	echanics of adhesion and delamination failures in bonded tubular joints	58
	3.8 M	odelling and simulation of adhesion failure and delamination damages	61
	3.8	3.1 Modelling approach	62
	3.8	3.2 Modelling of adhesion failure and delamination damages using	
		sublaminate technique	63
	3.9 Cr	iteria for onset and growth of failures in adhesive bonded tubular joints	64
	3.9	9.1 Onset of adhesion/delamination failures in adhesive bonded	
		tubular joints	65
	3.9	9.2 Growth of adhesion/delamination failures in adhesive bonded	
		tubular joints	66
		3.9.2.1 Computation of SERR using MCCI vis-à-vis VCCT	67
4	Adhesion	Failure Analyses of Bonded Tubular Single Lan Joints Made	
	with Lam	inated FRP Composites	71
			51
	4.1 Int	roduction	71
	4.2 Sp	ecimen geometry and boundary conditions	72
	4.3 Fi	nite element model validation	73
	4.4 Ef	fective overlap length of the bonded TSLJ	74
	4.5 Or	iset and growth of adhesion failures	75
	4.6 Re	sults and discussion	76
	4.0	5.1 Three-dimensional stress analyses	76
	4.0	5.2 Joint strength characteristics	/8
	4.0	5.5 Adhesion failure growth characteristics	/9
	4.0	5.4 Effect of phy-orientation on adhesion failure growth	80
	4.0	5.5 Effect of adherend anisotropy on adhesion failure growth	84 84
	4./ Su	minary and conclusions	ð4

5	Adhes	ion Failu	ire Anal	yses of Bonded Tubular Socket Joints Made	
	with L	Laminate	d FRP C	Composites	87
	51	Introduc	rtion		87
	5.2	Specime	en geome	try and boundary conditions	87
	5.3	Finite el	ement m	odel validation	89
	5.4	Suitable	ioint des	sign parameters of the bonded TSJ	89
	011	5.4.1 (Gan betw	veen the adherends	89
		5.4.2 F	Effective	coupling length	91
	5.5	Onset ar	nd growt	h of adhesion failures	94
	5.6	Results a	and discu	ission	95
		5.6.1	Three-dir	nensional stress analyses	95
		5.6.2 J	Joint stre	ngth characteristics	97
		5.6.3 A	Adhesion	failure growth characteristics	97
		5.6.4 E	Effect of	ply-orientation on adhesion failure growth	99
		5.6.5 E	Effect of	adherend/socket anisotropy on adhesion failure growth	103
	5.7	Summar	rv and co	nclusions	104
			J		
6	Delam	ination I	Damage	Analyses of Bonded Tubular Single Lap Joints Made	
	with L	Laminate	d FRP C	Composites	107
	61	Introduo	tion		107
	0.1 6 2	Specimo		try and houndary conditions	107
	0.2 6.2	Einite ol	amont m	adalling	100
	0.5 6 4	Onsot or	efficient in	odenning	109
	0. 4 6.5	Doculto a	and discu	asions	110
	0.5	651 T	Three dir	nonsional strass analyses	112
		652 I	Dolomina	tion damage growth characteristics	112
		0.3.2	5521	Delemination demage growth in individual adherende	113
			5 2 2	Detainination damage growth in both the adherende	114
		653 E	J.J.Z.Z	delemination damage growth on strong distributions	115
		0.5.5	n tha joir	at	117
		1	5 3 1	Delemination demage propagating in the outer adherend	11/
		C	5.5.5.1	only	117
		6	5 2 2	Delemination demage propagating in the inner adherend	11/
		l	5.5.2	Only	118
		6	5533	Delemination damages propagating in both the	110
		C	5.5.5	adherends	120
		654 F	Effect of	delamination damage growth on interlaminar stresses	120
		0.J.+ 1	n the add	perends	121
		1	5541	Delamination damage propagating in the outer adherend	121
			5.5.7.1	only	121
		6	5512	Delamination damage propagating in the inner adherend	121
		t	J.J. T . <u></u>	only	124
		6	5543	Delamination damages propagating in both the adherende	127
	66	Summar	ry and co	nelusions	120
	0.0	Summa		1010510115	120

X

7	Delaı with	nination Damage Analyses of Bonded Tubular Socket Joints Made Laminated FRP Composites	131
	7.1	Introduction	131
	7.2	Specimen geometry and boundary conditions	132
	7.3	Finite element modelling	133
	7.4	Onset and growth of delamination damages	134
	7.5	Results and discussion	135
		7.5.1 Three-dimensional stress analyses	135
		7.5.2 Delamination damage growth characteristics	136
		7.5.3 Effect of delamination damage growth on stress distributions	
		in the joint	137
		7.5.4 Effect of delamination damage growth on the interlaminar stresses	
		in the adherends	139
	7.6	Summary and conclusions	141

8 Adhesion Failure Analyses of Bonded Tubular Single Lap Joints Made with Functionally Graded Materials

143

165

8.1	Introduction	143
8.2	Specimen geometry and boundary conditions	144
8.3	Gradation of material properties of the adherends	145
	8.3.1 Material property gradation in the outer adherend	145
	8.3.2 Material property gradation in the inner adherend	147
8.4	Finite element modelling	149
	8.4.1 Effect of number of layers (M) used in FE mesh on stress	
	distributions in the joint	150
8.5	Results and discussion	155
	8.5.1 Effect of compositional gradient exponent (n) on	
	stress distributions in the joint	155
	8.5.2 Adhesion failure growth characteristics	156
	8.5.2.1 Effect of compositional gradient exponent (n) on the	
	SERR variations	157
	8.5.2.2 Effect of compositional gradient exponent (n) on stress	
	distributions in the joint	159
	8.5.3 Comparison of performances of the bonded TSLJ made with	
	laminated FRP composites and FGM adherends	161
	8.5.3.1 Comparison based on stress distributions in the joint	161
	8.5.3.2 Comparison based on SERR variations	163
8.6	Summary and conclusions	163

9 Adhesion Failure Analyses of Bonded Tubular Socket Joints Made with Functionally Graded Materials

9.1	Introduction	165
9.2	Specimen geometry and boundary conditions	166
9.3	Gradation of material properties of the socket and adherends	167

	9.4	Finite element modelling	168
		9.4.1 Effect of number of layers (M) on stress distributions in the joint	169
	9.5	Results and discussion	171
		9.5.1 Effect of compositional gradient exponent (n) on the stress	
		distributions in the joint	171
		9.5.2 Adhesion failure growth characteristics	172
		9.5.2.1 Effect of compositional gradient exponent (n) on the	
		SERR variations	173
		9.5.2.2 Effect of compositional gradient exponent (n) on the	
		stress distributions in the joint	174
		9.5.3 Comparison of performances of the bonded TSJ made	
		with laminated FRP composites and FGM adherends	177
		9.5.3.1 Comparison based on stress distributions in the joint	177
		9.5.3.2 Comparison based on SERR variations	179
	9.6	Summary and conclusions	180
10	Concl	usions and Scone for Further Work	183
10	Concl	usions and Scope for Further Work	183
10	Concl 10.1	usions and Scope for Further Work Summary	183 183
10	Concl 10.1 10.2	Summary Specific conclusions	183 183 184
10	Concl 10.1 10.2	Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made	183 183 184
10	Concl 10.1 10.2	Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites	183 183 184 184
10	Concl 10.1 10.2	Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.2 Delamination damage analyses of bonded TSLJs made	183 183 184 184
10	Concl 10.1 10.2	 Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.2 Delamination damage analyses of bonded TSLJs made with laminated FRP composites 	183 183 184 184 184
10	Concl 10.1 10.2	 Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.2 Delamination damage analyses of bonded TSLJs made with laminated FRP composites 10.2.3 Delamination damage analyses of bonded TSJs made 	 183 183 184 184 184
10	Concl 10.1 10.2	 Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.2 Delamination damage analyses of bonded TSLJs made with laminated FRP composites 10.2.3 Delamination damage analyses of bonded TSJs made with laminated FRP composites 	183 183 184 184 184 184 185
10	Concl 10.1 10.2	 Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.2 Delamination damage analyses of bonded TSLJs made with laminated FRP composites 10.2.3 Delamination damage analyses of bonded TSJs made with laminated FRP composites 10.2.4 Adhesion failure analyses of bonded TSLJs and TSJs made with 	 183 183 184 184 184 184 185
10	Concl 10.1 10.2	 Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.2 Delamination damage analyses of bonded TSLJs made with laminated FRP composites 10.2.3 Delamination damage analyses of bonded TSJs made with laminated FRP composites 10.2.4 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 	 183 183 184 184 184 185 186
10	Concl 10.1 10.2	 Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.2 Delamination damage analyses of bonded TSLJs made with laminated FRP composites 10.2.3 Delamination damage analyses of bonded TSJs made with laminated FRP composites 10.2.4 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.4 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.4 Adhesion failure analyses of bonded TSLJs and TSJs made with Functionally Graded Materials (FGMs) Scope for further work 	 183 183 184 184 184 184 185 186 186
10	Concl 10.1 10.2 10.3 10.4	 Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.2 Delamination damage analyses of bonded TSLJs made with laminated FRP composites 10.2.3 Delamination damage analyses of bonded TSJs made with laminated FRP composites 10.2.4 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.4 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.5 Delamination damage analyses of bonded TSLJs made with laminated FRP composites 10.2.6 Adhesion failure analyses of bonded TSLJs and TSJs made with Functionally Graded Materials (FGMs) Scope for further work Contributions from the present Thesis 	 183 183 184 184 184 185 186 186 188
10	Concl 10.1 10.2 10.3 10.4	 Summary Specific conclusions 10.2.1 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.2 Delamination damage analyses of bonded TSLJs made with laminated FRP composites 10.2.3 Delamination damage analyses of bonded TSJs made with laminated FRP composites 10.2.4 Adhesion failure analyses of bonded TSLJs and TSJs made with laminated FRP composites 10.2.4 Adhesion failure analyses of bonded TSLJs and TSJs made with functionally Graded Materials (FGMs) Scope for further work Contributions from the present Thesis 	 183 183 184 184 184 185 186 186 188

189

References

Publications from the Thesis

Appendix I Multi-Point Constraint elements (MPC 184)

Appendix II Contact or Gap element (CONTA 178)

VITAE