

TECHNICAL REPORT
RAPPORT TECHNIQUE
TECHNISCHER BERICHT

CEN/TR 17603-32-21

June 2022

ICS 49.025.50; 49.030.99; 49.140

English version

Space engineering - Adhesive bonding handbook

Ingénierie spatiale - Manuel de collage

Raumfahrttechnik - Handbuch zu geklebten
Verbindungen

This Technical Report was approved by CEN on 13 April 2022. It has been drawn up by the Technical Committee CEN/CLC/JTC 5.

CEN and CENELEC members are the national standards bodies and national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom.



**CEN-CENELEC Management Centre:
Rue de la Science 23, B-1040 Brussels**

Table of contents

European Foreword.....	27
1 Scope.....	28
2 References	29
3 Terms, definitions and abbreviated terms.....	30
3.1 Terms from other documents	30
3.2 Terms specific to the present document'.....	30
3.3 References	48
4 Joining.....	49
4.1 Joining methods for space structures.....	49
4.1.1 General	49
4.1.2 Adhesive bonding	49
4.1.3 Mechanical fastening disadvantages.....	50
4.2 References	51
4.2.1 General	51
4.2.2 ECSS documents.....	52
5 Adherends.....	53
5.1 Introduction.....	53
5.1.1 General	53
5.1.2 Polymer composites.....	54
5.1.3 Metals	54
5.1.4 Ceramics.....	55
5.2 Advanced composites.....	56
5.2.1 Polymer-based composites	56
5.2.2 FML - Fibre metal laminates.....	60
5.2.3 MMC - Metal matrix composites	60
5.3 Metals.....	61
5.3.1 Structural materials	61
5.3.2 New materials	61
5.4 Higher-temperature applications	62

5.4.1	Adherends	62
5.4.2	Adhesives	62
5.4.3	General guidelines	64
5.5	Low-temperature and cryogenic applications	64
5.5.1	Adherends	64
5.5.2	Adhesives	64
5.5.3	General guidelines	65
5.6	Bonds between adherends	65
5.6.1	General	65
5.6.2	Composite-to-composite	65
5.6.3	Composite-to-metal	66
5.6.4	Metal-to-metal	66
5.6.5	Dissimilar materials	66
5.7	References	67
5.7.1	General	67
5.7.2	ECSS documents	68
6	Adhesive characteristics and properties	69
6.1	Introduction	69
6.1.1	General	69
6.1.2	Guidelines	69
6.2	Types of adhesives	70
6.2.1	Formulation	70
6.2.2	Characteristics	70
6.2.3	Mechanical properties	73
6.2.4	Environmental durability	73
6.2.5	Aerospace structural adhesives	74
6.3	Epoxy-based adhesives	74
6.3.1	General	74
6.3.2	Properties	75
6.3.3	Environmental durability	80
6.4	Polyimide-based adhesives	84
6.4.1	General	84
6.4.2	Properties	85
6.5	Bismaleimide-based adhesives	87
6.5.1	General	87
6.5.2	Properties	87
6.6	Silicone-based adhesives	89

6.6.1	General	89
6.6.2	Properties	89
6.6.3	Environmental durability	91
6.7	Elastomeric adhesives	92
6.7.1	General	92
6.8	Adhesives used in space	92
6.8.1	Adhesive systems	92
6.9	References	96
6.9.1	General	96
6.9.2	Data sheets	97
6.9.3	Sources	98
6.9.4	ECSS documents	98
6.9.5	Other standards	98
7	Adhesive selection	99
7.1	Introduction	99
7.2	Adhesive selection factors	99
7.2.1	Guidelines	99
7.2.2	Evaluation exercise	99
7.2.3	Trade-off	100
7.3	Post application selection factors	101
7.3.1	Earth environment	101
7.3.2	Space environment	103
7.4	Pre-application selection factors	106
7.4.1	Joint design	106
7.4.2	Adhesive systems	106
7.4.3	Environmental factors	108
7.4.4	Cost factors	108
7.5	Application	109
7.5.1	Method	109
7.5.2	Cure factors	110
7.5.3	Health and safety	111
7.6	Adhesive screening criteria for space	112
7.7	References	113
7.7.1	General	113
7.7.2	ECSS documents	114
7.7.3	Other standards	115
8	Basic joint types	116

8.1	Introduction.....	116
8.2	Bond or mechanically fasten.....	116
8.2.1	General.....	116
8.2.2	Adhesive bonding in the space industry	118
8.3	Loading modes	118
8.4	Tensile shear loading.....	119
8.4.1	General.....	119
8.4.2	Joint geometry	120
8.4.3	Composite adherends	122
8.5	References	124
8.5.1	General.....	124
8.5.2	Sources.....	124
8.5.3	ECSS documents.....	125
9	Joint selection	126
9.1	Introduction.....	126
9.2	Joint strength.....	126
9.2.1	Failure modes	126
9.2.2	Guidelines.....	130
9.2.3	Joint design.....	131
9.3	Fatigue resistance	132
9.3.1	General.....	132
9.3.2	Joint evaluation	132
9.3.3	Factors influencing fatigue resistance	133
9.4	Acoustic fatigue resistance	135
9.4.1	Bonded carbon/epoxy composite joints	135
9.5	References	137
9.5.1	General.....	137
10	Theory and design practices	138
10.1	Introduction.....	138
10.1.1	Analysis	138
10.1.2	Factors of safety	138
10.2	Basic theories of bonded joints	138
10.2.1	Shear lag analysis.....	138
10.2.2	Linear-elastic stress-strain response.....	139
10.2.3	Non-linear stress-strain response.....	139
10.3	Environmental factors for bonded joints	144
10.3.1	Effect of temperature and moisture	144

10.4	Effect of bonding defects	148
10.4.1	General	148
10.4.2	Description of bonding defects	148
10.4.3	NDT non-destructive techniques	156
10.5	Double lap and double strap joints	158
10.5.1	Stress distribution	158
10.6	Single lap joints	162
10.6.1	General	162
10.6.2	Load path eccentricity	162
10.6.3	Joint efficiencies	162
10.6.4	Adhesive characteristics	165
10.7	Double-sided stepped lap joints	165
10.7.1	Joint strength	165
10.7.2	Adherend stiffness balance	165
10.8	Single-sided stepped lap joints	168
10.8.1	Joint strength	168
10.9	Scarf joints	168
10.9.1	Joint strength	168
10.10	Calculation of bonded joint strength	169
10.11	Analysis of joint configurations	169
10.11.1	Analytical notation	169
10.11.2	Single lap shear joint	170
10.11.3	Double lap shear joint	173
10.11.4	Double-lap shear joint under mechanical and temperature loads	175
10.11.5	Single taper scarf joint	183
10.11.6	Double taper scarf joint	184
10.11.7	Stepped lap joint	185
10.11.8	Analysis of environmental factors	186
10.12	Analytical design tools	187
10.12.1	General	187
10.12.2	Commercial software	187
10.12.3	In-house software	187
10.13	ESAComp®	187
10.13.1	Background	187
10.13.2	Usage and scope	188
10.13.3	Analysis and data	188
10.14	Astrum: Example spreadsheet	191

10.14.1 General	191
10.14.2 Usage and scope	191
10.14.3 Analysis and data.....	191
10.15 ESDU data and software	194
10.15.1 General	194
10.15.2 ESDU 78042: Bonded joints - 1.....	194
10.15.3 ESDU 79016: Bonded joints – 2.....	195
10.15.4 ESDU 80011: Bonded joints – 3.....	196
10.15.5 ESDU 80039: Bonded joints – 4.....	196
10.15.6 ESDU 81022: Bonded joints – 5.....	197
10.16 Design chart	198
10.16.1 Aide memoire.....	198
10.16.2 Joint category.....	198
10.17 References	201
10.17.1 General	201
10.17.2 ECSS documents.....	203
10.17.3 Other standards	203
11 Design allowables	204
11.1 Introduction.....	204
11.2 Single lap joint	205
11.2.1 Static loading	205
11.2.2 Dynamic loading	209
11.3 Double lap joint.....	211
11.3.1 Static loading	211
11.4 Symmetrical double scarf joint	212
11.4.1 Static loading	212
11.4.2 Dynamic loading	214
11.5 References	216
11.5.1 General	216
11.5.2 ECSS documents.....	216
12 Surface preparation.....	217
12.1 Introduction.....	217
12.1.1 General	217
12.1.2 Standard processes	218
12.1.3 Development processes.....	219
12.1.4 Process steps	219
12.1.5 Legislation.....	219

12.2 Composites: Thermosetting matrix	219
12.2.1 General	219
12.2.2 Techniques	220
12.2.3 Abrasion.....	220
12.2.4 Peel ply	222
12.3 Composites: Thermoplastic matrix	222
12.3.1 General	222
12.3.2 Proposed methods.....	223
12.4 Aluminium alloys.....	224
12.4.1 Aerospace aluminium alloys.....	224
12.4.2 MMC and Al-Lithium alloys.....	224
12.4.3 Optimised Forest Products Laboratory (FPL) etch.....	225
12.4.4 Phosphoric acid anodising (PAA)	227
12.4.5 Chromic acid anodising (CAA)	227
12.4.6 Boric sulphuric acid anodising (BSAA)	228
12.4.7 Thin film sulphuric acid anodising (TFSAA).....	231
12.4.8 Solvent vapour cleaning	231
12.4.9 Development processes	232
12.5 Titanium alloys.....	233
12.5.1 General	233
12.5.2 Acid or alkali etch.....	234
12.5.3 Non-chromium proprietary process	235
12.6 References	235
12.6.1 General	235
12.6.2 ECSS documents.....	237
13 Bonding methods	238
13.1 Introduction.....	238
13.1.1 Basic methods	238
13.1.2 Adhesives	238
13.1.3 Composite structures	239
13.2 Co-curing.....	240
13.2.1 Applications.....	240
13.2.2 Loading	242
13.2.3 Adhesives	242
13.2.4 Tooling	243
13.3 Secondary bonding.....	243
13.3.1 General	243

13.3.2 Adhesives	243
13.3.3 Tooling	244
13.4 Applying adhesives	244
13.4.1 Film adhesives	244
13.4.2 Paste adhesives.....	245
13.4.3 Manufacturing processes	248
13.5 Manufacturing factors for adhesives	249
13.5.1 General.....	249
13.5.2 Product-specific factors	249
13.6 Bondline integrity	251
13.6.1 General	251
13.6.2 Manufacturing-related factors.....	251
13.7 Thermal bonding thermoplastic composites	251
13.7.1 General.....	251
13.7.2 Direct bonding	252
13.7.3 Thermabond process	252
13.7.4 Welding techniques	253
13.8 Rapid adhesive bonding (RAB).....	253
13.8.1 General	253
13.8.2 Applications.....	253
13.8.3 Materials	253
13.8.4 Process.....	255
13.8.5 Equipment.....	255
13.8.6 Carbon fibre reinforced composites.....	256
13.8.7 Joint strength	257
13.9 References	257
13.9.1 General	257
13.9.2 ECSS documents.....	257
14 Quality assurance.....	258
14.1 Introduction.....	258
14.1.1 Documentation.....	258
14.1.2 Standards	258
14.1.3 Aerospace applications	258
14.2 Quality system	259
14.2.1 General	259
14.3 Specifications	259
14.3.1 Procurement	259

14.3.2	Incoming inspection	260
14.3.3	Design.....	260
14.3.4	Processes	260
14.3.5	Materials	261
14.3.6	Training personnel	262
14.4	Check lists	262
14.4.1	Material procurement	262
14.4.2	Bonded joints	266
14.5	References	268
14.5.1	General	268
14.5.2	ECSS documents.....	268
15	Test methods	269
15.1	Introduction.....	269
15.1.1	Use of test methods	269
15.1.2	Adhesives for space use	269
15.1.3	Characterisation of adhesives	271
15.1.4	Assessment of adhesive bonding process	272
15.1.5	Test methods and standards.....	273
15.2	Tensile tests for adhesives	274
15.2.1	General	274
15.2.2	Adhesive evaluation	274
15.2.3	Sandwich panels: Flatwise tensile strength	275
15.3	Shear tests for adhesives	275
15.3.1	General	275
15.3.2	Napkin ring.....	275
15.3.3	Thick adherend single lap	276
15.3.4	Single lap	276
15.3.5	Double lap.....	278
15.3.6	Cracked lap shear (CLS).....	280
15.4	Cleavage of adhesives	281
15.4.1	General	281
15.4.2	Specimen geometry	281
15.4.3	Typical test results	284
15.4.4	Calculation of fracture strength.....	285
15.4.5	Loading	287
15.5	Bond durability by wedge test	287
15.5.1	General	287

15.5.2	Test specimen and configuration.....	287
15.5.3	Results and analysis	289
15.6	Peel tests.....	289
15.6.1	General	289
15.6.2	Climbing drum peel test for adhesives.....	290
15.6.3	T-peel test.....	291
15.6.4	Floating roller peel.....	291
15.7	Fatigue resistance	292
15.7.1	Fatigue properties of adhesives	292
15.7.2	Fatigue resistance of bonded joints.....	293
15.7.3	Acoustic fatigue.....	295
15.8	Creep resistance	295
15.8.1	Adhesive properties	295
15.8.2	Test methods	296
15.9	Environmental resistance.....	296
15.9.1	Earth	296
15.9.2	Space.....	296
15.10	References	297
15.10.1	General	297
15.10.2	ECSS documents.....	299
15.10.3	Other standards	299
16	Inspection.....	300
16.1	Introduction.....	300
16.2	Role of inspection	300
16.2.1	General	300
16.2.2	Quality control and inspection	300
16.2.3	Non-destructive testing	301
16.3	Defects	301
16.3.1	Bonded joints	301
16.3.2	Adhesion	301
16.3.3	Cohesive properties of adhesives	302
16.3.4	Significance of defects	302
16.4	Inspection techniques	304
16.4.1	Commonly-used techniques	304
16.4.2	Developments	305
16.5	Ultrasonic	306
16.5.1	Applications.....	306

16.5.2 Limitations	306
16.5.3 C-scan	306
16.5.4 Leaky Lamb waves (LLW)	307
16.5.5 Acousto-ultrasonic	308
16.6 Radiography	308
16.6.1 Application	308
16.6.2 Limitations	308
16.6.3 X-radiography	309
16.7 Mechanical impedance: Bond testers	309
16.7.1 Application	309
16.7.2 Limitations	309
16.7.3 Principle	309
16.7.4 Fokker bond tester	310
16.7.5 Acoustic flaw detector	310
16.8 Holography	311
16.8.1 Application	311
16.8.2 Limitations	311
16.8.3 Principle	311
16.9 Thermography	311
16.9.1 Application	311
16.9.2 Limitations	311
16.9.3 Principle	312
16.10 Acoustic emission	312
16.10.1 Application	312
16.10.2 Limitations	312
16.10.3 Principle	313
16.11 References	313
16.11.1 General	313
16.11.2 ECSS documents	315
17 Materials for repairs	316
17.1 Introduction	316
17.1.1 General	316
17.1.2 Repair procedures	316
17.1.3 Repair levels	316
17.1.4 Basic features of bonded repairs	317
17.1.5 Objective of repair	317
17.1.6 Materials	317

17.1.7	Design.....	318
17.1.8	Quality assurance	318
17.2	Parent adherends	320
17.2.1	Materials	320
17.2.2	Sandwich structures.....	320
17.3	Repair patches	320
17.3.1	Materials	320
17.4	Adhesives.....	321
17.4.1	General.....	321
17.4.2	Structural	321
17.4.3	Splice	321
17.4.4	Fillers and mastics	322
17.4.5	Potting compounds	322
17.4.6	Properties	322
17.4.7	Repair adhesive selection factors.....	323
17.5	References	324
17.5.1	General	324
17.5.2	ECSS documents.....	325
18	Design of repairs	326
18.1	Introduction.....	326
18.1.1	Basic categories of repair.....	326
18.1.2	General design concepts.....	327
18.1.3	Composite repair design concepts	329
18.1.4	Sandwich panels, laminates and sheet metal.....	330
18.1.5	Cracked metal components.....	330
18.2	Concepts for laminates	330
18.2.1	General.....	330
18.2.2	Flush repairs	330
18.2.3	External repairs.....	331
18.3	Concepts for sandwich panels	331
18.3.1	Repair objectives	331
18.3.2	Field level repairs	332
18.4	Design parameters: Thin skin constructions.....	334
18.4.1	Design principles.....	334
18.5	Design parameters: Crack patching metals.....	336
18.5.1	Principles	336
18.6	References	337

18.6.1	General	337
18.6.2	ECSS documents	337
19 Repair techniques		338
19.1	Introduction	338
19.2	Surface preparation	338
19.2.1	General	338
19.2.2	Guidelines	339
19.2.3	Paint removal	340
19.2.4	Composite adherends	340
19.2.5	Metal adherends: Tank processes	341
19.2.6	Metal adherends: Non-tank processes	341
19.2.7	Use of chemical processes	343
19.3	Repair procedures	343
19.3.1	Basic methods	343
19.3.2	Standard procedures	344
19.3.3	Example: Sandwich panel repair	344
19.4	Equipment	347
19.4.1	Tools	347
19.4.2	Process equipment	347
19.4.3	Hot bonding equipment	347
19.4.4	Facilities	347
19.4.5	Selection of equipment	347
19.5	References	348
19.5.1	General	348
20 Test and inspection of repairs		350
20.1	Introduction	350
20.1.1	Testing	350
20.1.2	Inspection	350
20.2	Testing	350
20.2.1	Adhesive acceptance tests	350
20.2.2	Durability of bonded repairs	351
20.3	Inspection	351
20.3.1	General	351
20.3.2	In-service damage	351
20.3.3	Calibration	353
20.3.4	Standards	353
20.3.5	Guidelines on NDT sensitivity	353

20.4	Pre-repair inspection.....	354
20.4.1	Damage assessment	354
20.4.2	Guidelines.....	355
20.4.3	Selection of NDT technique.....	355
20.5	Post-repair inspection	356
20.5.1	Repair verification	356
20.5.2	Guidelines.....	357
20.5.3	Selection of NDT technique.....	357
20.6	References	358
20.6.1	General.....	358
20.6.2	ECSS documents.....	359
21	Case studies on bonded connections	360
21.1	Introduction.....	360
21.1.1	General.....	360
21.1.2	Assembly processes	360
21.1.3	Manufacturing processes	360
21.1.4	Case studies	360
21.2	Aluminium alloy end fittings for CFRP tubes	361
21.2.1	Source	361
21.2.2	Application	361
21.2.3	Objective of study	361
21.2.4	Parameters for design.....	363
21.2.5	Manufacture	366
21.2.6	Inspection	367
21.2.7	Conclusions	367
21.2.8	Comments on case study.....	367
21.3	LVA launch vehicle attachment ring and CFRP thrust cone	368
21.3.1	Source	368
21.3.2	Application	368
21.3.3	Objective of study	368
21.3.4	Concept	368
21.3.5	Joint design and analysis	368
21.3.6	Manufacture	371
21.3.7	Assembly	371
21.3.8	Inspection	371
21.3.9	Test.....	372
21.3.10	Conclusions	372

21.3.11	Comments on case study.....	372
21.4	Shuttle pallet satellite (SPAS) primary framework structure	372
21.4.1	Source	372
21.4.2	Application	373
21.4.3	Objective of study	373
21.4.4	Concept	373
21.4.5	Materials	373
21.4.6	General requirements and overall design description.....	374
21.4.7	Joint design analysis	374
21.4.8	Manufacturing	377
21.4.9	Bonding process	377
21.4.10	Test.....	377
21.4.11	Inspection	378
21.4.12	Conclusions	378
21.4.13	Comments	378
21.5	MD 11 outboard flap vane.....	378
21.5.1	Source	378
21.5.2	Application	379
21.5.3	Objective of the study.....	379
21.5.4	Parameters for design.....	379
21.5.5	Concept	379
21.5.6	Materials	380
21.5.7	Joint design.....	381
21.5.8	Manufacturing	383
21.5.9	Test.....	383
21.5.10	Inspection	384
21.5.11	Conclusions	384
21.5.12	Comments on case study.....	384
21.6	CFRP-titanium tubular bonded joint.....	384
21.6.1	Source	384
21.6.2	Application	385
21.6.3	Objective of study	385
21.6.4	Parameters for design.....	385
21.6.5	Concept	385
21.6.6	Materials	386
21.6.7	Joint design.....	387
21.6.8	Analysis	387

21.6.9	Manufacture	390
21.6.10	Test.....	391
21.6.11	Inspection	393
21.6.12	Conclusions	393
21.6.13	Comments on case study	393
21.7	Ariane 5 ACY 5400 upper payload extension ring.....	394
21.7.1	Source	394
21.7.2	Application	394
21.7.3	Objective	394
21.7.4	Concept	395
21.7.5	Joint design and analysis	396
21.7.6	Manufacture	399
21.7.7	Assembly	401
21.7.8	Inspection	401
21.7.9	Test.....	401
21.7.10	Conclusions	403
21.7.11	Comments on case study	405
21.8	SRM - solid rocket motors: Flexible joints	405
21.8.1	Source	405
21.8.2	Application	405
21.8.3	Objective of study	406
21.8.4	Parameters for design.....	406
21.8.5	Concept	408
21.8.6	Materials	408
21.8.7	Joint design.....	409
21.8.8	Analysis	409
21.8.9	Manufacture	410
21.8.10	Test.....	411
21.8.11	Inspection	412
21.8.12	Comments on case study	412
21.9	References	413
21.9.1	General	413
22	Case studies on bonded structural materials	414
22.1	Introduction.....	414
22.1.1	General	414
22.1.2	Sandwich structures.....	414
22.1.3	Metal laminates	415

22.2 CFRP central cylinder for satellites	415
22.2.1 Source	415
22.2.2 Application	415
22.2.3 Objective of study	415
22.2.4 Parameters for design.....	415
22.2.5 Concept	416
22.2.6 Materials	419
22.2.7 Joint design.....	420
22.2.8 Manufacture	423
22.2.9 Test.....	424
22.2.10 Inspection	425
22.2.11 Analysis	425
22.2.12 Conclusions	426
22.2.13 Comments on case study.....	426
22.3 Filament wound thrust cylinder	427
22.3.1 Source	427
22.3.2 Application	427
22.3.3 Objective of study	427
22.3.4 Parameters for design.....	427
22.3.5 Concept	427
22.3.6 Materials	428
22.3.7 Design.....	429
22.3.8 Joint design.....	429
22.3.9 Analysis	430
22.3.10 Manufacture	430
22.3.11 Test.....	432
22.3.12 Inspection	432
22.3.13 Conclusions	432
22.3.14 Comments on case study.....	432
22.4 Ariane 4 payload adapter 937B.....	433
22.4.1 Source	433
22.4.2 Application	433
22.4.3 Objective of study	433
22.4.4 Parameters for design.....	433
22.4.5 Concept	434
22.4.6 Materials	434
22.4.7 Design.....	435

22.4.8 Joint design.....	435
22.4.9 Analysis	436
22.4.10 Manufacturing	438
22.4.11 Test.....	439
22.4.12 Inspection	439
22.4.13 Conclusions	439
22.4.14 Comments on case study.....	440
22.5 Galileo radiation shielding.....	440
22.5.1 Source	440
22.5.2 Application	440
22.5.3 Objective of the study.....	440
22.5.4 Parameters for design.....	440
22.5.5 Concept	441
22.5.6 Materials	441
22.5.7 Design.....	443
22.5.8 Analysis	444
22.5.9 Manufacturing	444
22.5.10 Test.....	445
22.5.11 Inspection	445
22.5.12 Conclusions	445
22.5.13 Comments on case study.....	445
22.6 References	446
22.6.1 General.....	446

Figures

Figure 6.3-1 - Epoxy-based Araldite AV 138M adhesive system: Environmental resistance (DCB tests)	82
Figure 6.3-2 - Epoxy-based Araldite AV 138M adhesive system: Environmental resistance (lap shear tests)	83
Figure 6.6-1 - Silicone-based adhesives: Temperature performance.....	91
Figure 7.2-1 - Adhesive selection factors.....	100
Figure 7.3-1 – Environment: Elevated temperature response of adhesive lap joints	102
Figure 8.4-1 - Tensile shear: Single lap joint.....	120
Figure 8.4-2 – Composite adherends: Orientation of surface fibre	123
Figure 9.2-1 – Joint strength: Relationship between peel and shear stresses and their effect on bond strength with increasing adherend thickness.....	128
Figure 9.2-2 - Joint strength: Use of different bonded joint types	129
Figure 9.3-1 - Fatigue resistance study: Bonded joint configurations	133

Figure 9.4-1 - Random vibration resistance study: Bonded joint configurations	136
Figure 10.2-1 - Adhesive in non-linear shear: Stress-strain response.....	140
Figure 10.2-2 - Adhesive in non-linear shear: Models and characteristics	141
Figure 10.2-3 – Bonded joints: Non-uniform stress and strain distribution	142
Figure 10.2-4 – PABST programme: Design overlaps used in skin splices.....	143
Figure 10.3-1 – Bonded joints: Effect of moisture on stress distributions	145
Figure 10.3-2 – Bonded joints: Influence of moisture absorption and desorption on peak adhesive shear strains	146
Figure 10.3-3 – Bonded joints: Effect of progressive moisture absorption on bond strain ...	147
Figure 10.4-1 - Bonded joints: Examples of acceptable bond flaw sizes.....	149
Figure 10.4-2 - Bonded joints: Typical quality zoning.....	150
Figure 10.4-3 – Double overlap bonded joint: Adhesive shear stresses (defect-free)	151
Figure 10.4-4 - Double overlap bonded joint: Adhesive stresses with edge disbond.....	152
Figure 10.4-5 - Double overlap bonded joint: Adhesive stresses with away from edge disbond	152
Figure 10.4-6 - Double overlap bonded joint: Adhesive stresses with central disbond	153
Figure 10.4-7 - Adhesive bonded joints: Effect of disbond flaws on flexibility	154
Figure 10.4-8 – Adhesive thickness: Variation of peak induced adhesive stress at ends of bonded joint overlap	155
Figure 10.5-1 - Double lap and strap joints: Reducing peel stresses	159
Figure 10.5-2 - Double lap and strap joints: Effect of overlap on maximum adhesive shear strains	160
Figure 10.5-3 - Double lap joints: Design factors	161
Figure 10.6-1 - Joint efficiency for single lap composite joints: Ductile adhesive	163
Figure 10.6-2 - Joint efficiency for single lap composite joints: Brittle adhesive	164
Figure 10.7-1 - Double-sided stepped lap joints: Adherend stiffness balance	166
Figure 10.7-2 - Double-sided stepped lap joints: Design optimisation.....	167
Figure 10.11-1 - Analysis: Notation for symmetrical single-lap shear joint	170
Figure 10.11-2 - Analysis: Notation for single-lap joint R-degree peeling.....	171
Figure 10.11-3 - Θ degree peeling strength	172
Figure 10.11-4 - Analysis: Notation for double-lap shear joint.....	173
Figure 10.11-5 - Analysis: Notation for double lap joint (standard overlap length)	175
Figure 10.11-6 - Shear stress distribution versus the adhesive length for single lap joint without eccentricity	175
Figure 10.11-7 - Stress concentration factor as a function of correlation factor with stiffness ratio parameter.....	177
Figure 10.11-8 - Shear stress distribution for large overlap lengths	179
Figure 10.11-9 - Stress concentration factor for large overlap lengths	180
Figure 10.11-10 – UD CFRP-HT: Shear stress distribution versus the normalised bond length	181

Figure 10.11-11 – Quasi-isotropic CFRP-HT: Shear stress distribution versus the normalised bond length	182
Figure 10.11-12 - Analysis: Notation for single taper scarf joint	183
Figure 10.11-13 - Analysis: Notation for symmetrical double tapered scarf joint	184
Figure 10.11-14 - Analysis: Notation for stepped lap joint (recessed and simple)	185
Figure 10.11-15 - Analysis: Notation for recessed and simple scarf joints (four or more steps)	186
Figure 10.13-1 – ESAComp: Double lap joint - example of stresses in the adhesive layer (non-linear adhesive model)	189
Figure 10.13-2 – ESAComp: Double lap joint - example of stresses in the adhesive layer (linear adhesive model)	190
Figure 10.14-1 – Astrium example spread-sheet: Fatigue data, determined by analysis.....	192
Figure 10.14-2 – Astrium example spread-sheet: Joint design (new).....	193
Figure 10.16-1 – Design chart: Aide memoire ‘factors to consider’	199
Figure 10.16-2 – Design chart: Example of joint category procedure	200
Figure 11.2-1 - Design curve: Static loaded single lap joint with CFRP/epoxy adherends...	205
Figure 11.2-2 - Design curve: Static loaded single lap joint with CFRP/epoxy-to-steel adherends	206
Figure 11.2-3 - Design curve: Static loaded single lap joint with CFRP/epoxy-to-steel adherends	207
Figure 11.2-4 - Design curve: Static loaded single lap joint - joint strength versus overlap length for CFRP/epoxy and CFRP/epoxy-to-steel adherends	207
Figure 11.2-5 - Design curve: Static loaded single lap joint - joint strength versus overlap length for CFRP/epoxy adherends	208
Figure 11.2-6 - Design curve: Static compression loaded single lap joint (stabilised sandwich, lower bond) - joint strength versus overlap length for CFRP/epoxy adherends	208
Figure 11.2-7 - Design curve: Single lap joint - tension fatigue S-N curve at RT for CFRP/epoxy adherends	209
Figure 11.2-8 - Design curve: Single lap joint - tension fatigue S-N curve at 180 °C for CFRP/epoxy adherends	210
Figure 11.3-1 - Design curve: Static loaded double lap joint for CFRP/epoxy to titanium adherends	211
Figure 11.4-1 - Design curve: Static loaded double scarf joint for CFRP/epoxy to titanium adherends.....	212
Figure 11.4-2 - Design curve: Static loaded double scarf joint for CFRP/epoxy to titanium adherends.....	213
Figure 11.4-3 - Design curve: Double scarf joint tension fatigue S-N curve for CFRP/epoxy to titanium adherends.....	214
Figure 11.4-4 - Design curve: Double scarf joint tension fatigue S-N curve for CFRP/epoxy to titanium adherends.....	215
Figure 11.4-5 - Design curve: Double scarf joint tension fatigue S-N curve for CFRP/epoxy to titanium adherends.....	215

Figure 12.2-1 - Thermosetting matrix composites: An abrasion surface preparation method	221
Figure 12.2-2 - Thermosetting matrix composites: A simple abrasion surface preparation method	221
Figure 12.4-1 - Aluminium alloy surface preparation: FPL etch process	226
Figure 12.4-2 - Aluminium alloy surface preparation: Phosphoric acid anodise (PAA) process	227
Figure 12.4-3 - Aluminium alloy surface preparation: Chromic acid anodise (CAA) process	228
Figure 12.4-4 - Aluminium alloy surface preparation: Boric/sulphuric acid anodise (BSAA) process.....	230
Figure 12.4-5 - Aluminium honeycomb preparation: Solvent vapour cleaning.....	231
Figure 12.4-6 – Surface preparation: Processes applied to aluminium alloys within the aerospace sector.....	232
Figure 12.5-1 - Titanium alloy surface preparation: Etching	234
Figure 12.5-2 - Titanium alloy surface preparation: Pasa Jell 107C®	235
Figure 13.2-1 - Diagram of co-curing joints for composites: With and without an adhesive layer	241
Figure 13.2-2 - Reticulating film adhesive during cure	243
Figure 13.4-1 - Hand operated applicator for one-part paste adhesives	246
Figure 13.4-2 - Hand operated proportioning machine for two-part paste adhesives	247
Figure 13.4-3 - Typical application route for film and paste adhesives	248
Figure 13.8-1 - Rapid adhesive bonding (RAB) equipment.....	256
Figure 15.2-1 - ASTM D-897: Metal test specimen	275
Figure 15.3-1 - ASTM D-0229: Napkin ring shear test	276
Figure 15.3-2 - ASTM D-1002: Single lap test specimen	277
Figure 15.3-3 - ASTM D-3165: Single lap test specimen	278
Figure 15.3-4 - ASTM D-3528: Double lap test specimen.....	279
Figure 15.3-5 - Cracked lap shear (CLS) test specimen	280
Figure 15.4-1 - ASTM D-3433: Cleavage - flat adherend specimen.....	282
Figure 15.4-2 - ASTM D-3433: Cleavage – CDCB contoured double cantilever beam specimen.....	283
Figure 15.4-3 - ASTM D-3433: Flat adherend test result chart.....	284
Figure 15.4-4 - ASTM D-3433: Contoured double cantilever beam test result chart	285
Figure 15.5-1 - ASTM D-3762: Wedge test specimen	288
Figure 15.6-1 - ASTM D1781 climbing drum peel test	290
Figure 15.6-2 - ASTM D-1876 T-peel test specimen.....	291
Figure 15.6-3 - ASTM D-3167 floating roller peel test.....	292
Figure 15.7-1 - Examples of fatigue test specimens	294
Figure 16.3-1 - Maximum permissible local defect.....	303

Figure 18.3-1 - Sandwich panel repair concepts.....	332
Figure 18.3-2 - Field level sandwich panel repair concepts	333
Figure 18.4-1 - Design parameters: Thin skin constructions	335
Figure 19.2-1 - Surface preparation for repairs to aluminium alloys: PANTA process	341
Figure 19.2-2 - Surface preparation for repairs to aluminium alloys: PACS process equipment set-up	342
Figure 19.3-1 – Example: Sandwich panel repair procedure	345
Figure 20.3-1 - Example of NDT Instrument sensitivity: Bonded metal constructions	354
Figure 21.2-1 - Case study: CFRP tube/Al alloy - Joint design for tubular specimens and end fittings.....	364
Figure 21.2-2 - Case study: CFRP tube/Al alloy - Bonding procedure for end fittings	366
Figure 21.3-1 - Case study: LVA ring/CFRP thrust cone - Basic construction of thrust cone assembly	369
Figure 21.3-2 - Case study: LVA ring/CFRP thrust cone - Joint configurations for LVA ring to thrust cone connection	370
Figure 21.4-1 - Case study: SPAS-01 primary structure	374
Figure 21.4-2 - Case study: SPAS - details of joint dimensions	376
Figure 21.5-1 - Case study: MD 11 outboard flap vane - basic structure	380
Figure 21.5-2 - Case study: MD 11 outboard flap vane - skin lay-up and joints.....	381
Figure 21.5-3 - Case study: MD 11 outboard flap vane - ribs.....	382
Figure 21.5-4 - Case study: MD 11 outboard flap vane - splice joint analysis	382
Figure 21.6-1 - Case study: CFRP Tube/titanium fitting - bonded joint section	385
Figure 21.6-2 - Case study: CFRP tube/titanium fitting - tensile stress distribution in adhesive layer.....	388
Figure 21.6-3 - Case study: CFRP tube/titanium fitting - tensile stress distribution in composite.....	389
Figure 21.6-4 - Case study: CFRP tube/titanium fitting - peel stress distribution in adhesive layer and composite external ply	389
Figure 21.6-5 - Case study: CFRP/titanium end-fitting - analytical notation	390
Figure 21.6-6 - Case study: CFRP/titanium end-fitting - manufacturing procedure	391
Figure 21.6-7 - Case study: CFRP/titanium end fitting - bonded joint failure mechanism ...	393
Figure 21.7-1 – Case study: Ariane 5 ACY 5400 - location.....	395
Figure 21.7-2 – Case study: Ariane 5 ACY 5400 - concept.....	395
Figure 21.7-3 – Case study: Ariane 5 ACY 5400 - sectional view of bonded joint	397
Figure 21.7-4 – Case study: Ariane 5 ACY 5400 - effect of bondline thickness	398
Figure 21.7-5 – Case study: Ariane 5 ACY 5400 - example of (half) FE model for joint	399
Figure 21.7-6 – Case study: Ariane 5 ACY 5400 - witness sample under test	402
Figure 21.8-1 – Case study: SRM – position of fflexible joints	406
Figure 21.8-2 – Case study: SRM flexible joints – example design approach.....	407
Figure 21.8-3 – Case study: SRM – example of flexible joint concept.....	408

Figure 21.8-4 – Case study: SRM – example of flexible joint design.....	409
Figure 22.2-1 - Case study: CFRP central cylinder - structural elements	418
Figure 22.2-2 - Case study: CFRP Central cylinder - lower ring joint	420
Figure 22.2-3 - Case study: CFRP central cylinder - edge inserts	421
Figure 22.2-4 - Case study: CFRP central cylinder - tank interface inserts	422
Figure 22.2-5 - Case study: CFRP central cylinder - shear panel interface cleats.....	423
Figure 22.3-1 - Case study: Filament wound thrust cylinder - joint design: Tank interface and end ring.....	430
Figure 22.3-2 - Case study: Filament wound thrust cylinder - manufacturing sequence	431
Figure 22.4-1 - Case study: Ariane 4 payload adapter - overall view of adapter 937B	434
Figure 22.4-2 - Case study: Ariane 4 payload adapter - end ring joint	436
Figure 22.5-1 - Case study: Galileo radiation shielding - laminate design.....	444

Tables

Table 4.1-1 - Adhesively bonded aerospace structures: Examples.....	50
Table 5.2-1 - Polymer-based composite adherends	58
Table 5.2-2 - Metal matrix composite adherends under evaluation	60
Table 5.3-1 - Metal adherends: Currently used or undergoing evaluation.....	61
Table 5.4-1 - Adhesive bonding of materials: High temperature performance.....	63
Table 6.2-1 - Classification of adhesives: General characteristics and properties	71
Table 6.2-2 - Classification of adhesives: Typical shear and peel strength characteristics	73
Table 6.3-1 - Epoxy-based film adhesives: Properties	76
Table 6.3-2 - Epoxy-based paste and liquid adhesives: Properties.....	79
Table 6.3-3 - Epoxy-based adhesives: Environmental durability assessment	80
Table 6.3-4 - Epoxy-based film adhesives: Cytec FM 300-2M and FM 96-U: CTE and shear modulus, determined by TGA and DMA	84
Table 6.4-1 - Polyimide-based film adhesives: Properties	86
Table 6.5-1 - Bismaleimide-based film adhesives: Properties.....	88
Table 6.6-1 - Silicone-based paste and liquid adhesives: Properties	90
Table 6.8-1 – Adhesive systems used in space: Examples	93
Table 7.3-1 - Adhesives: Typical maximum use temperatures.....	104
Table 7.5-1 - Typical cure schedules for aerospace structural adhesives	110
Table 7.6-1 - Adhesive selection criteria: Based on bulk property testing.....	113
Table 8.2-1 - Comparison of joining methods: Fastening and bonding	117
Table 8.3-1 - Basic loading modes in adhesive bonds.....	119
Table 8.4-1 - Types and geometry for adhesive bonded joints.....	121
Table 8.4-2 – Composite adherends: Typical transverse (90°) tensile strengths for some aerospace carbon-reinforced UD products	124

Table 9.3-1 - Fatigue resistance study: Factors relating to resistance of adhesively bonded joints.....	134
Table 10.4-1 - Bonded joints: Description of NDT methods	157
Table 10.4-2 - Bonded joints: Detection methods for various defects	158
Table 10.15-1 - ESDU data items for bonded joints.....	194
Table 11.1-1 – Design curves: Summary of bonded joint configurations.....	204
Table 12.3-1 - Surface Preparation: Proposed methods for thermoplastic composites	223
Table 12.4-1 - Al-Li alloys and SiC particle MMC: Evaluation of surface preparation methods	225
Table 12.4-2 – Surface preparation: Development processes	233
Table 13.1-1 - Comparison between co-curing and secondary bonding as an assembly technique for composite structures.....	239
Table 13.2-1 - Co-curing methods for composites: With and without an adhesive layer.....	241
Table 13.5-1 - Manufacturing factors for adhesives	250
Table 13.7-1 - Thermoplastic matrix composites: Welding techniques.....	252
Table 13.8-1 - Rapid adhesive bonding (RAB): Adherends	254
Table 13.8-2 - Rapid adhesive bonding (RAB): Adhesives	254
Table 14.4-1– Procurement check-list: Paste adhesives – summary	264
Table 14.4-2 – Procurement check-list: Film adhesives – summary	265
Table 14.4-3 – Check list: Adhesive bonding	267
Table 15.1-1 - Adhesive screening: Example of US federal specifications.....	271
Table 15.1-2 – Test methods and standards: Summary	273
Table 15.9-1- Environmental durability in space: Standard test methods.....	297
Table 16.4-1 - NDT Techniques: Summary of defect detection capability	305
Table 17.1-1 - Bonded repairs: Examples of applications and materials	319
Table 17.4-1 - Repair adhesives types: Grouped by cure and service temperatures	323
Table 18.1-1 - Basic design concepts for repairs	328
Table 18.3-1 - Field level sandwich panel repairs: Comparison of design concepts.....	334
Table 18.5-1 - Design parameters: Crack patching metal components	336
Table 19.2-1 - Bonded repairs: Surface preparation	339
Table 19.3-1 - Basic methods for bonded repairs	344
Table 19.4-1 - Use of equipment for bonded repairs.....	348
Table 20.4-1 - Pre-repair defect inspection methods	356
Table 20.5-1 - Post-repair defect inspection methods.....	358
Table 21.2-1 - Case study: CFRP tube/Al alloy - Material selection concept design study	362
Table 21.2-2 - Case study: CFRP tube/Al alloy - Material selection detail design study.....	365
Table 21.4-1 - Case study: SPAS - Material selection/design study for SPAS-01 framework	373

Table 21.5-1 - Case study: MD 11 outboard flap vane - materials	380
Table 21.6-1 - Case study: CFRP tube/titanium fitting - material properties.....	386
Table 21.6-2 - Case study: CFRP/titanium end-fitting - stiffness analysis results.....	390
Table 21.7-1 – Case study: Ariane 5 ACY 5400 - potential adhesives	400
Table 21.7-2 – Case study: Ariane 5 - typical static load case	403
Table 21.7-3 - Case study: Ariane 5 ACY 5400 - comparison between bonded and riveted assembly	404
Table 22.2.1 - Case study: CFRP central cylinder - trade-off between design concepts	417
Table 22.2.2 - Case study: CFRP central cylinder - structural analysis stiffness results	425
Table 22.2.3 - Case study: CFRP central cylinder - mass analysis.....	426
Table 22.3-1 - Case study: Filament wound thrust cylinder - design parameters	427
Table 22.3-2 - Case study: Filament wound thrust cylinder - materials	428
Table 22.4-1 - Case study: Ariane 4 payload adapter - materials	435
Table 22.4-2 - Case study: Ariane 4 payload adapter - margin of safety for failure mode analysis	437
Table 22.4-3 - Case study: Ariane 4 payload adapter - manufacturing development summary	438
Table 22.5-1 - Case study: Galileo radiation shielding - estimated radiation levels	440
Table 22.5-2 - Case study: Galileo radiation shielding - design criteria.....	441
Table 22.5-3 - Case study: Galileo radiation shielding - concepts.....	441
Table 22.5-4 - Case study: Galileo radiation shielding - materials	442
Table 22.5-5 - Case study: Galileo radiation shielding - properties for Al-Ta-Al bonded joints	443

European Foreword

This document (CEN/TR 17603-32-21:2022) has been prepared by Technical Committee CEN/CLC/JTC 5 "Space", the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-32.

This Technical report (CEN/TR 17603-32-21:2022) originates from ECSS-E-HB-32-21A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

1

Scope

This handbook is an acceptable way of meeting the requirements of adhesive materials in bonded joints of ECSS-E-ST-32.

2

References

Due to the structure of the document, each clause includes at its end the references called in it.