



BSI Standards Publication

Space engineering — Structural materials handbook

Part 6: Fracture and material modelling, case studies and design and integrity control and inspection.

National foreword

This Published Document is the UK implementation of CEN/TR 17603-32-06:2022.

The UK participation in its preparation was entrusted to Technical Committee ACE/68, Space systems and operations.

A list of organizations represented on this committee can be obtained on request to its committee manager.

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

© The British Standards Institution 2022
Published by BSI Standards Limited 2022

ISBN 978 0 539 127 9 7

ICS 49.140

Compliance with a British Standard cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 June 2022.

Amendments/corrigenda issued since publication

Date	Text affected
------	---------------

TECHNICAL REPORT

CEN/TR 17603-32-06

RAPPORT TECHNIQUE

TECHNISCHER BERICHT

January 2022

ICS 49.140

English version

Space engineering - Structural materials handbook - Part 6: Fracture and material modelling, case studies and design and integrity control and inspection

Ingénierie spatiale - Manuel des matériaux structuraux
- Partie 6 : Modélisation des matériaux et de leur
rupture, études de cas, inspections et contrôle de
l'intégrité

Raumfahrttechnik - Handbuch zu Strukturmaterialien -
Teil 6: Modellierung von Brüchen und Materialien -
Fallstudien, Design, Integritätskontrolle, Inspektionen

This Technical Report was approved by CEN on 29 November 2021. It has been drawn up by the Technical Committee CEN/CLC/JTC 5.

CEN and CENELEC members are the national standards bodies and national technical 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	25
Introduction	26
64 Behaviour of advanced composites	27
64.1 Introduction.....	27
64.2 Summary of material behaviour	28
64.2.1 Metal matrix composites.....	28
64.2.2 Inorganic ceramic matrix composites	29
64.3 Significant behavioural characteristics	29
64.3.1 General.....	29
64.3.2 Modulus mismatch	29
64.3.3 Matrix-to-reinforcement interface.....	30
64.3.4 In-situ fibre strength	31
64.3.5 CTE mismatch	31
64.3.6 Thermal history and residual stresses.....	32
64.3.7 Multiple cracking	32
64.3.8 Thermo-mechanical Fatigue (TMF)	32
64.4 Basic fracture characteristics	32
64.4.1 General.....	32
64.4.2 Particulate reinforced MMC.....	33
64.4.3 Fibre reinforced MMC	34
64.4.4 Fibre reinforced CMC.....	35
64.4.5 Defining design values	35
64.5 Failure criteria for CMC.....	36
64.5.1 Introduction	36
64.5.2 Design aspects	36
64.6 References	39
64.6.1 General.....	39
65 Particulate reinforced metals	40
65.1 Introduction.....	40
65.1.1 Materials	40

65.1.2	Composites	40
65.1.3	Particulate reinforcement	41
65.2	Damage mechanisms	42
65.2.1	Unnotched specimen	42
65.2.2	Notched specimen	43
65.2.3	Influence of particles	43
65.2.4	Composite performance	44
65.3	Failure modes and fracture behaviour	44
65.3.1	Matrix effects	44
65.3.2	Failure mode studies	45
65.3.3	Particulate shape and aspect ratio	45
65.3.4	Particulate fracture	47
65.3.5	Void nucleation and growth	47
65.3.6	Fracture toughness	48
65.4	Thermo-mechanical fatigue (TMF) and creep	49
65.4.1	Residual stresses	49
65.4.2	Temperature	49
65.4.3	Superplasticity	49
65.4.4	Applications	49
65.5	References	49
65.5.1	General	49
66	Fibre reinforced metals	52
66.1	Introduction	52
66.1.1	Materials	52
66.2	Damage mechanisms	53
66.2.1	General	53
66.2.2	Effect of lay-up	53
66.3	Failure modes	54
66.3.1	General	54
66.3.2	Matrix dominated failure	54
66.3.3	Fibre-dominated damage	54
66.3.4	Self-similar damage growth	54
66.3.5	Fibre-matrix interfacial failures	55
66.4	Thermo-mechanical and creep response	55
66.4.1	General	55
66.4.2	Application	56
66.5	References	56

66.5.1	General.....	56
67	Inorganic ceramic matrix composites	58
67.1	Introduction.....	58
67.1.1	General.....	58
67.1.2	Matrix.....	59
67.1.3	Interface.....	59
67.1.4	Fibres.....	59
67.2	Damage mechanisms.....	59
67.2.1	Material effects.....	59
67.2.2	Microcracking.....	59
67.2.3	Porosity.....	61
67.2.4	Manufacturing and in-service effects.....	62
67.2.5	Crack propagation.....	62
67.3	Fracture behaviour.....	63
67.3.1	Toughness parameters	63
67.3.2	Test specimens.....	68
67.3.3	'R' curves	68
67.4	References	70
68	Modelling advanced materials.....	71
68.1	Introduction.....	71
68.1.1	Polymer composites.....	71
68.1.2	Metal matrix composites.....	71
68.1.3	Inorganic ceramic matrix materials.....	71
68.1.4	Summary of models.....	72
68.2	Particulate reinforced metals	73
68.2.1	Use of models.....	73
68.3	Fibre reinforced metals	73
68.3.1	Use of models.....	73
68.4	Inorganic ceramic matrix composites.....	74
68.4.1	Use of models.....	74
68.5	References	77
68.5.1	General.....	77
69	High-temperature structures	79
69.1	Introduction.....	79
69.1.1	Applications.....	79
69.1.2	Performance	79

69.1.3	High-temperature materials	79
69.1.4	Development approach	80
69.2	Functions	80
69.2.1	General	80
69.2.2	Aerodynamic heating	81
69.2.3	Propulsive power generation	82
69.3	Operating environments	83
69.4	Integration	83
69.5	Heat management	84
69.6	Life expectancy	84
69.6.1	General	84
69.6.2	Launcher	84
69.6.3	Spaceplane	84
69.6.4	Satellite	85
69.7	Materials selection	85
69.8	Manufacturing	85
69.9	Applications	86
69.9.1	Future reusable launch vehicles	86
69.9.2	Flight-vehicle dependent	87
69.9.3	Non-vehicle dependent	91
69.9.4	Summary of European capabilities	94
69.10	References	95
69.10.1	General	95
70	Thermo-structural designs	97
70.1	Introduction	97
70.1.1	General	97
70.1.2	Single mission	97
70.1.3	Reusable vehicles	98
70.2	Spaceplanes	98
70.2.1	Hermes	98
70.2.2	HOPE	98
70.2.3	Single- and two-stage-to-orbit	99
70.3	Hermes	99
70.4	HOPE	100
70.5	HOTOL	104
70.6	SÄNGER	106
70.7	National aerospace plane (NASP)	107

70.8 Demonstrator panels	109
70.8.1 General	109
70.8.2 NASP	109
70.9 Nose cones	109
70.9.1 General	109
70.9.2 Shuttle orbiter	109
70.9.3 Hermes	111
70.9.4 HOPE	113
70.9.5 NASP	113
70.9.6 HOTOL	113
70.9.7 SÄNGER	114
70.9.8 X-38	114
70.10 Wing leading edges (WLE)	115
70.10.1 General	115
70.10.2 Shuttle orbiter	115
70.10.3 Buran	115
70.10.4 Hermes	117
70.10.5 HOPE	118
70.10.6 Others	118
70.11 Box sections	119
70.11.1 NASP	119
70.11.2 Hermes	119
70.12 Cryogenic tanks	120
70.13 Heat shield designs	120
70.14 Air inlet-intakes	123
70.15 Earth re-entry capsules	124
70.16 Manned re-entry vehicles	126
70.17 Deep space missions	127
70.17.1 CNSR ROSETTA: Earth return capsule	127
70.18 Mars landers	128
70.18.1 General	128
70.18.2 NASA Pathfinder/MESUR network landers	128
70.18.3 MARSNET	129
70.19 Cassini-Huygens	129
70.19.1 General	129
70.19.2 C-C aerobrake (heat shield)	129
70.19.3 Nose cap front shield with AQ60	130

70.20	Planetary probes	130
70.21	Aerobrake designs.....	130
70.21.1	General.....	130
70.21.2	NASA/ESA Cassini-Huygens mission	130
70.22	PRORA: USV – unmanned space vehicle	132
70.22.1	Background.....	132
70.22.2	USV programme	133
70.22.3	USV systems and flight test beds.....	134
70.22.4	External configuration of FTB_1 and FTB_2.....	135
70.22.5	External configuration of FTB_3.....	136
70.23	X-38 Body flap	138
70.23.1	Background.....	138
70.23.2	Body flaps	140
70.23.3	Mechanical fasteners	141
70.23.4	CMC to metal attachment.....	142
70.23.5	Ceramic bearings.....	143
70.23.6	Ceramic seals	144
70.24	X-38 Nose cap.....	145
70.24.1	Background.....	145
70.24.2	Concept	146
70.24.3	Thermal profiles	146
70.24.4	Flexible insulation design	147
70.24.5	Integration and qualification testing	148
70.24.6	Summary	150
70.25	Aerobrake: Deployable CMC decelerator.....	151
70.25.1	Background	151
70.25.2	Mars ISRU mission ‘in-situ resource unit’	152
70.25.3	Mars ISRU mission – Concept	152
70.25.4	Mars ISRU mission – Environmental aspects.....	155
70.26	References	155
70.26.1	General.....	155
71	Thermal protection systems	160
71.1	Introduction.....	160
71.1.1	Application	160
71.1.2	European development programmes	161
71.1.3	Concepts.....	162
71.1.4	Non load-carrying TPS.....	164

71.1.5	Load-carrying TPS	164
71.1.6	Reusable structures	165
71.2	Cooling modes.....	166
71.2.1	General.....	166
71.2.2	Passive TPS	166
71.2.3	Active cooling concepts.....	167
71.3	Early re-entry capsules	168
71.4	Ablative designs	170
71.4.1	General.....	170
71.4.2	Programmes	171
71.4.3	Materials	171
71.5	Space Shuttle orbiter	174
71.5.1	General.....	174
71.5.2	Materials and configurations	175
71.5.3	In-Service TPS Performance.....	179
71.6	Buran.....	179
71.6.1	General.....	179
71.6.2	Materials and configurations	181
71.7	Advanced carbon reinforced composites	181
71.7.1	Carbon-carbon composites	181
71.7.2	ACC - Advanced carbon-carbon.....	181
71.7.3	Aerospatiale - Aerotiss®	182
71.7.4	Carbon-silicon carbide composites.....	183
71.8	Durable metallic TPS	185
71.8.1	General.....	185
71.8.2	Multiwall TPS	186
71.8.3	Developments	187
71.9	Titanium-based composites	189
71.9.1	IASP	189
71.10	Internal multiscreen insulation (IMI)	189
71.10.1	Concept	189
71.10.2	Development and characterisation	192
71.10.3	Potential applications	194
71.11	Flexible external insulation (FEI).....	195
71.11.1	General.....	195
71.11.2	Design concept	195
71.11.3	Key features.....	195

71.11.4	Product range	196
71.11.5	Hermes	197
71.11.6	MSTP programme.....	198
71.11.7	ARD programme	201
71.11.8	Future reusable vehicles	201
71.11.9	Verified performance.....	202
71.11.10	IFI - Internal flexible insulation development.....	203
71.12	CMC shingles	205
71.12.1	Hermes design concept	205
71.12.2	TETRA/X-38 programme panels	207
71.12.3	SPFI - Surface protected flexible insulation	209
71.13	Heat pipes	220
71.13.1	General.....	220
71.13.2	Shuttle-type heat pipe cooled wing leading edge	222
71.13.3	Sodium-Hastelloy-X heat pipe for advanced space transportation system	222
71.13.4	Refractory metal-CMC heat pipe for NASP	223
71.14	Cooled panels.....	224
71.14.1	General.....	224
71.14.2	Demonstrator units.....	225
71.14.3	Active cooling on NASP	226
71.15	Beryllium TPS.....	228
71.15.1	General.....	228
71.15.2	Cassini-Huygens heat shield: Phase A configuration	228
71.16	Aerobrakes	230
71.17	Heat shields.....	230
71.17.1	General.....	230
71.17.2	SEPCORE® TPS concept.....	230
71.17.3	Ceramic heatshield assembly (CHA).....	231
71.17.4	MIRKA - Micro re-entry capsule	239
71.17.5	ALSCAP - Alternative low-cost, short-manufacturing-cycle ceramic assessment programme.....	241
71.18	Aeroshell	244
71.18.1	General.....	244
71.18.2	Semi-integrated aeroshell TPS (S.I.A.T)	244
71.18.3	Demonstrator aeroshell design.....	244
71.19	Cryogenic tanks.....	250
71.19.1	General.....	250

71.19.2 European programmes	251
71.19.3 Concepts: TPS panel array	252
71.19.4 Concepts: LH tank cryogenic insulation.....	252
71.20 TPS mass budgets	254
71.20.1 Allocation	254
71.20.2 Examples	255
71.21 TPS verification	255
71.22 Polymer foam cryogenic insulation	255
71.22.1 General.....	255
71.22.2 Polymer foam characteristics	255
71.22.3 Properties	256
71.22.4 Materials	257
71.22.5 Ranking of polymer foam cryogenic insulation	259
71.22.6 Further work.....	261
71.23 High temperature insulation (HTI).....	261
71.23.1 Background.....	261
71.23.2 Development factors	262
71.23.3 Development approach	263
71.23.4 Materials	266
71.23.5 Testing	266
71.23.6 Summary	270
71.24 References	270
72 SPF/DB titanium designs	280
72.1 Introduction.....	280
72.1.1 General.....	280
72.1.2 Aircraft components	280
72.1.3 Space applications	280
72.2 Basic SPF/DB process	281
72.2.1 Superplastic forming	281
72.2.2 Diffusion bonding	281
72.3 Process attributes.....	283
72.4 Titanium alloys.....	284
72.5 Aluminium alloys.....	285
72.6 Access doors and ducting.....	286
72.6.1 General.....	286
72.6.2 Slat track/jack cans	286
72.6.3 Underwing access doors.....	287

72.6.4	Other SPF/DB components	288
72.7	Spars and stiffened panels	288
72.8	Struts and cylinders	289
72.9	Leading edges and lateral fins	289
72.10	Firewalls	290
72.11	Pressure vessels	290
72.12	Cost aspects	291
72.13	European facilities	291
72.14	References	291
72.14.1	General	291
73	Propulsion technologies	293
73.1	Introduction	293
73.2	Propulsion unit requirements	293
73.2.1	Launcher engines	293
73.2.2	Shuttle engines	293
73.2.3	Spaceplane engines	293
73.2.4	Thrusters	294
73.2.5	Nozzles	294
73.3	Fuels	294
73.3.1	General	294
73.3.2	Solid propellants	294
73.3.3	LH/LOX	294
73.3.4	Monopropellants	295
73.3.5	Bipropellants	295
73.4	Ariane 5	295
73.4.1	General	295
73.4.2	MPS solid rocket motor	295
73.5	Vulcain engine	296
73.5.1	General	296
73.5.2	Specification	297
73.5.3	Materials	297
73.6	HM 7 engine	298
73.6.1	General	298
73.6.2	Nozzle geometry	299
73.7	Mage 2 motor	299
73.8	Nozzles	299
73.9	Space Shuttle Main Engine (SSME)	300

73.10	Air breathing engines.....	300
73.10.1	General.....	300
73.10.2	NASP nozzle development.....	301
73.10.3	European ramjet technology	301
73.11	CMC rocket stator.....	301
73.12	Metal thrusters.....	303
73.13	CMC thrusters	303
73.14	References	303
73.14.1	General.....	303
74	Protective coatings	306
74.1	Introduction.....	306
74.2	Coating functions.....	307
74.2.1	General.....	307
74.2.2	Application requirements.....	308
74.3	Passivation	308
74.3.1	General.....	308
74.3.2	Materials	309
74.3.3	Coating adhesion	309
74.4	Basic coating types.....	310
74.4.1	General.....	310
74.4.2	Diffusion coatings.....	310
74.4.3	Overlay coatings	310
74.5	Coating processes.....	311
74.5.1	General.....	311
74.5.2	Slurry coating.....	311
74.5.3	Physical vapour deposition (PVD).....	311
74.5.4	Enhanced physical vapour deposition (PVD).....	312
74.5.5	Thermal spraying	312
74.5.6	Chemical vapour deposition (CVD).....	312
74.5.7	Enhanced chemical vapour deposition (CVD).....	313
74.5.8	Other processes.....	313
74.6	Coatings: Titanium components.....	314
74.6.1	NASP	314
74.7	Coatings: Superalloy components	314
74.7.1	General.....	314
74.7.2	Aluminide diffusion coatings.....	315
74.7.3	MCrAlY overlay coatings.....	315

74.8 Thermal barrier coatings (TBC).....	316
74.8.1 Ni-based superalloy components	316
74.8.2 Shuttle Main Engine HPFTP blades	316
74.8.3 Fibre-reinforced TBC's	317
74.8.4 Coating technology	317
74.8.5 Seals.....	317
74.9 Carbon-Carbon: Oxidation protection.....	317
74.9.1 General.....	317
74.9.2 Applications.....	317
74.9.3 Coating systems	317
74.9.4 Basic problem	318
74.10 Multiplex coatings	318
74.10.1 General.....	318
74.10.2 Constituents.....	319
74.10.3 Application examples	320
74.11 Coatings: C-SiC and SiC-SiC	321
74.11.1 General.....	321
74.11.2 C-SiC	321
74.11.3 SiC-SiC.....	321
74.12 Carbon-Carbon: Surface coatings.....	322
74.12.1 Dimensionally stable structures.....	322
74.13 References	326
74.13.1 General.....	326
75 Seal technology	330
75.1 Introduction.....	330
75.1.1 Uses	330
75.1.2 Structural assemblies.....	330
75.1.3 Dynamic seals.....	331
75.1.4 Materials	331
75.2 Structural seals.....	331
75.3 Seal materials.....	332
75.3.1 General.....	332
75.3.2 Elastomers.....	332
75.3.3 Types of elastomers.....	335
75.3.4 Viscoelasticity	339
75.3.5 Physical properties.....	340
75.3.6 Chemical properties	347

75.3.7	Rubber-to-metal bonding.....	350
75.3.8	Engineering design with elastomers.....	351
75.3.9	Finite element analysis.....	354
75.3.10	Applications.....	356
75.3.11	Thermoplastic elastomers	357
75.4	Energised metal seals	357
75.4.1	General.....	357
75.4.2	Materials	358
75.5	NASP engine developments	359
75.5.1	General.....	359
75.5.2	Developments	359
75.6	Fibrous seals	360
75.7	Elastomeric seals.....	361
75.7.1	Materials	361
75.7.2	Design aspects	361
75.7.3	Causes of leakage	362
75.7.4	Aerospace applications	363
75.8	References	364
75.8.1	General.....	364
75.8.2	ECSS standards	365
75.8.3	ASTM standards	366
75.8.4	ISO standards	366
76	Integrity control of high temperature structures	367
76.1	Introduction.....	367
76.2	Materials.....	367
76.2.1	Integrity control	367
76.2.2	Fracture control.....	368
76.3	Failure characteristics.....	368
76.3.1	Advanced alloy systems.....	368
76.3.2	Composite materials	368
76.4	High temperature	369
76.5	Coatings	369
76.5.1	General.....	369
76.5.2	Manufacturing	369
76.5.3	Inspection	369
76.6	Considerations.....	370
76.6.1	Mass optimisation	370

76.6.2	Approach	370
76.7	Case study: Developments in integrity control	371
76.8	Case study: Phase 1 - Material characterisation	373
76.8.1	General	373
76.8.2	Materials, manufacturing and NDT	373
76.8.3	Defect detection by selected NDI methods	374
76.8.4	Maximum applied stresses	375
76.8.5	High-temperature tests	376
76.8.6	Residual strengths	377
76.8.7	Analysis	377
76.8.8	Conclusions	377
76.9	Case study: Phase 2 - Structural sub-component behaviour	378
76.10	References	378
76.10.1	General	378
77	Defect types	379
77.1	Introduction	379
77.2	Advanced metal alloys	380
77.2.1	General	380
77.2.2	ODS alloys	380
77.2.3	SPF alloys	380
77.3	Metal matrix composites	380
77.3.1	General	380
77.3.2	Standard product forms	380
77.3.3	Near-net shape manufacture	381
77.4	Ceramic matrix composites	382
77.5	Coatings	382
77.6	Joints	383
77.6.1	General	383
77.6.2	Uses	383
77.6.3	Mechanical fastened joints	384
77.6.4	Fusion joints	384
77.7	Structural parts	385
77.7.1	General	385
77.7.2	Composite materials	385
77.8	In service	385
77.9	References	387
77.9.1	General	387

78 Damage tolerance	388
78.1 Introduction.....	388
78.1.1 Materials	388
78.1.2 Structure	388
78.1.3 Fracture mechanics.....	388
78.1.4 Initial material quality (IMQ).....	388
78.2 MMC: Particulate and whisker reinforced.....	389
78.2.1 Fatigue behaviour	389
78.2.2 Fracture mechanics.....	390
78.3 CMC: Whisker reinforced.....	391
78.4 MMC: Continuous fibre reinforced	391
78.4.1 Fatigue.....	391
78.5 CMC: Continuous fibre reinforced.....	393
78.5.1 Failure characteristics	393
78.6 Coatings	394
78.6.1 Coating performance.....	394
78.6.2 Process and material selection	395
78.6.3 Failure characteristics	395
78.7 References	396
78.7.1 General.....	396
78.7.2 ECSS standards	396
79 Fracture control	397
79.1 Introduction.....	397
79.1.1 Application	397
79.2 References	397
79.2.1 General.....	397
79.2.2 ECSS standards	397
80 NDT techniques	398
80.1 Introduction.....	398
80.2 Advanced metal alloys.....	399
80.2.1 General.....	399
80.2.2 Brittle materials	399
80.2.3 Multi-phase microstructures	399
80.3 Metal matrix composites	399
80.4 Carbon-Carbon and ceramic matrix composites	400
80.5 Coatings	403
80.6 Joints.....	403

80.6.1	General	403
80.6.2	Fused joints	403
80.6.3	Mechanically fastened and interlock joints	404
80.7	Fusion joints	404
80.7.1	General	404
80.7.2	Thin-walled seam welded tubes	404
80.7.3	Diffusion bonded joints	405
80.8	References	405
80.8.1	General	405
81	High-temperature testing	408
81.1	Introduction	408
81.2	Purpose of testing	408
81.3	Material behaviour	409
81.3.1	Basic fracture modes	409
81.3.2	Metal matrix composites	409
81.3.3	Inorganic and ceramic matrix composites	409
81.4	Degradation mechanisms	410
81.4.1	Materials	410
81.4.2	Degradation rate	410
81.5	Coupon testing	411
81.5.1	General	411
81.5.2	Single-fibre tests	411
81.5.3	Fibre push through	411
81.5.4	Net-shape components	411
81.5.5	Flexural and ILSS testing	411
81.5.6	Small coupon tests	412
81.5.7	Machining	412
81.5.8	Extensometry	412
81.5.9	End tabs	413
81.5.10	Coatings	413
81.5.11	Material gradation	413
81.5.12	Specimen alignment	413
81.5.13	Linear elasticity	413
81.6	Mechanical properties	413
81.6.1	General	413
81.6.2	Tensile	414
81.6.3	Compression	415

81.6.4	Shear	416
81.6.5	Open-hole tension.....	416
81.6.6	Fatigue.....	416
81.7	Fracture toughness.....	416
81.8	Physical properties	417
81.8.1	General.....	417
81.8.2	Standards	417
81.9	Status of test standards	417
81.9.1	General.....	417
81.9.2	Metal matrix composites.....	418
81.9.3	Ceramic matrix composites	418
81.10	Demonstrator testing	422
81.11	References	423
81.11.1	General.....	423

Figures

Figure 64.4-1	- Representative stress-strain curve: Particulate reinforced MMC.....	33
Figure 64.4-2	- Representative stress-strain curves: Monofilament reinforced MMC	34
Figure 64.4-3	- Representative stress-strain curves: Bidirectional SiC-SiC composite.....	35
Figure 64.5-1	- Failure criteria: Comparison between predicted failure curves for.....	37
Figure 64.5-2	- Failure criteria: ‘Hour-glass’ test specimen for C-C/SiC composites	38
Figure 65.2-1	- Relative stress-strain behaviours of optimised (good) and non- optimised (poor) MMCp composites	43
Figure 65.3-1	- Features of particles in MMCp materials	46
Figure 65.3-2	- Possible crack propagation paths in MMCp materials	47
Figure 67.2-1	- Glass matrix composite material: Microcracking sequence.....	61
Figure 67.2-2	- Bidirectional glass-ceramic matrix composite: Schematic of tunnelling cracks in 90° layers	62
Figure 67.3-1	- Schematic representations of load-displacement (<i>P/u</i>) curves: (a) Linear elastic behaviour	64
Figure 67.3-2	- Schematic representations of load-displacement (<i>P/u</i>) curves: (b) Linear non-elastic behaviour	64
Figure 67.3-3	- Schematic representations of load-displacement (<i>P/u</i>) curves: (c) Non-linear elastic behaviour	65
Figure 67.3-4	- Schematic representations of load-displacement (<i>P/u</i>) curves: (d) Non-linear non-elastic behaviour.....	65
Figure 67.3-5	- CMC materials: Possible fracture mechanisms	66
Figure 67.3-6	- SENB and delamination test specimens.....	68
Figure 67.3-7	- Fracture energy (<i>J</i> , Rice) as a function of crack increment: Short random fibre materials.....	69

Figure 67.3-8 - Fracture energy (J , Rice) as a function of crack increment: Multidirectional materials	69
Figure 70.4-1 - HOPE: Distribution of surface temperatures	100
Figure 70.4-2 - HOPE: Distribution of TPS	101
Figure 70.4-3 - HOPE structural materials to be applied	102
Figure 70.4-4 - OREX structure and TPS	103
Figure 70.4-5 - HYFLEX: Structural Configuration	103
Figure 70.5-1 - HOTOL: Configuration 'g'	104
Figure 70.5-2 - HOTOL: Rear Fuselage and Aft LOX Tank	106
Figure 70.6-1 - SÄNGER: Surface temperatures at Mach 6.8	107
Figure 70.7-1 - NASP: Basic configuration	108
Figure 70.9-1 - Shuttle: Nose cap system components	110
Figure 70.9-2 - Shuttle: RCC chin panel system components	111
Figure 70.9-3 - Hermes: C-C INOX® nose cone (0.6 scale)	112
Figure 70.9-4 - HOPE: Heat resistant structural configuration	113
Figure 70.9-5 - HOTOL: Nose cone and nose shell	114
Figure 70.10-1 - Shuttle orbiter: Wing leading edge system components	115
Figure 70.10-2 - Buran: Wing leading edge construction	116
Figure 70.10-3 - Buran: Temperature of wing leading edge with time	117
Figure 70.10-4 - Hermes: Hot structure leading edge	118
Figure 70.11-1 - Hermes: C-SiC box for thermal structure	119
Figure 70.13-1 - Double wall heat shield	121
Figure 70.13-2 - Heat shield and stringer stiffened panels	122
Figure 70.13-3 - MARSNET: Heat shield for planetary entry probe	123
Figure 70.14-1 - Air intake ramp in C-SiC	124
Figure 70.15-1 - COMET recovery system	125
Figure 70.15-2 - MIRKA capsule: Exploded view of spherical heat shield	126
Figure 70.16-1 - ACRV flight vehicle: General layout	127
Figure 70.17-1 - CNRS ROSETTA: Aerocapsule configuration	128
Figure 70.19-1 - Huygens: C-C decelerator design	129
Figure 70.19-2 - Huygens: Nose cap front shield	130
Figure 70.21-1 - Cassini-Huygens: Stretched carbon skin decelerator	131
Figure 70.21-2 - Cassini-Huygens: Separation sequence	131
Figure 70.22-1 - PRORA – USV: FTB_2 external configuration	136
Figure 70.22-2 – VEGA launcher: Large fairing	137
Figure 70.22-3 - PRORA – USV: FTB_3 external configuration	138
Figure 70.23-1 – X-38: Test vehicle	139
Figure 70.23-2 – X-38 body flap: Construction	140

Figure 70.23-3 – X-38 body flap: Mechanical fasteners	141
Figure 70.23-4 – X-38 body flap: CMC to metal attachment	143
Figure 70.23-5 – X-38 body flap: Ceramic bearing	144
Figure 70.23-6 – X-38 body flap: Ceramic dynamic seal.....	145
Figure 70.24-1 – X-38 Nose assembly	146
Figure 70.24-2 - X-38 Nose assembly: Thermal profiles	147
Figure 70.24-3 – X-38 Nose assembly: Flexible insulation distribution	148
Figure 70.24-4 – X-38 Nose assembly: Flexible insulation assembly.....	149
Figure 70.24-5 – X-38 Nose cap with insulation mounted on vehicle nose structure.....	151
Figure 70.25-1 – Deployable CMC hot structures - Mars ISRU mission.....	154
Figure 71.2-1 - TPS concepts.....	166
Figure 71.2-2 - Principal passive thermal control architectures.....	167
Figure 71.3-1 - Galileo entry probe.....	169
Figure 71.4-1 - Ablatives: Basic decomposition mechanisms	170
Figure 71.4-2 - CARINA: General layout	172
Figure 71.5-1 - Orbiter: Design surface temperatures (°C) in ascent and re-entry trajectories	174
Figure 71.5-2 - Orbiter: TPS - Thermal protection systems.....	175
Figure 71.5-3 - Orbiter: RSI system configuration.....	178
Figure 71.6-1 - BURAN: External thermal protection	180
Figure 71.7-1 - TPS: ACC multi-post stand-off concept	182
Figure 71.8-1 - TPS: Multiwall panel scheme	186
Figure 71.10-1 - TPS: IMI design concept	191
Figure 71.11-1 - TPS: Schematic of FEI blanket.....	195
Figure 71.11-2 - TPS: IFI internal flexible insulation blanket.....	204
Figure 71.11-3 - TPS: IFI blanket configuration in X-38 nose cap.....	205
Figure 71.12-1 - TPS: Hermes CMC shingle support cross-section.....	206
Figure 71.12-2 – SPFI surface protected flexible insulation panel	210
Figure 71.12-3 – SPFI Surface protected flexible insulation: Design.....	211
Figure 71.12-4 – SPFI: Summary of thermal performance.....	213
Figure 71.12-5 – SPFI: Thermal performance during vehicle re-entry and landing	214
Figure 71.12-6 – SPFI: Structural performance - Shaker test	216
Figure 71.12-7 – SPFI: Structural performance – spectral distribution and OASPL	217
Figure 71.12-8 – SPFI: SHEFEX TPS demonstrator	220
Figure 71.13-1 - Heat pipe: Operation principle for leading edge cooling.....	221
Figure 71.13-2 - Heat pipe: Wing leading edge design for advanced space transportation system	223
Figure 71.13-3 - Heat pipe: NASP wing leading edge.....	224

Figure 71.14-1 - Convective cooling systems	225
Figure 71.14-2 - Cooled structure: Design concepts.....	226
Figure 71.14-3 - NASP: SiC-Ti-Titanium aluminide D-groove panel.....	227
Figure 71.15-1 - Cassini-Huygens: Exploded view	229
Figure 71.15-2 - Cassini-Huygens: Beryllium TPS design solution	229
Figure 71.17-1 - CHA - Ceramic heatshield assembly	233
Figure 71.17-2 – CHA: Insulation and bolt assembly	234
Figure 71.17-3 – CHA-element: Temperature profiles during full mission testing.....	238
Figure 71.17-4 – MIRKA/FOTON: Configuration.....	240
Figure 71.18-1 – Aeroshell: Design concept.....	244
Figure 71.18-2 – Aeroshell: SIAT test model assembled cross-section	245
Figure 71.18-3 – Aeroshell: Down-scaled demonstrator design features	246
Figure 71.19-1 – TPS panel array concept: Cryogenic tanks.....	252
Figure 71.19-2 – Cryogenic insulation: LH tank concepts.....	254
Figure 71.23-1 - TPS: Flow diagram of HTI development testing for X-38 nose cap assembly.....	265
Figure 71.23-2 - TPS: HTI temperature gradient test set-up, parameters and sample configuration	269
Figure 72.2-1 - SPF/DB: Two sheet configuration.....	281
Figure 72.2-2 - SPF/DB: Three sheet configuration	282
Figure 72.2-3 - SPF/DB: Four sheet configuration	283
Figure 72.4-1 - Superplastic forming: Strain rate sensitivity in formability trials on Ti alloy IMI 834.....	285
Figure 72.6-1 - SPF/DB titanium alloy: Slat track and jack for Airbus A310	287
Figure 72.6-2 - SPF/DB Ti: A310 underwing access door locations.....	288
Figure 72.9-1 - SPF/DB: Principle of four-sheet technique for leading edge	290
Figure 73.5-1 - Vulcain engine: Schematic diagram	296
Figure 73.6-1 - Ariane 4 HM 7 engine: Thrust chamber.....	298
Figure 73.10-1 - NASP: Modified government baseline engine configuration	301
Figure 73.11-1 - Rocket stator CMC components.....	302
Figure 74.3-1 - Coatings: Properties of coating, substrate and interface.....	309
Figure 74.10-1 - Multiplex coatings: Basic configuration.....	319
Figure 74.10-2 - C-C multiplex coatings: Crack and sealing mechanisms	320
Figure 74.12-1 – Coatings: Dimensionally stable carbon-carbon – concept.....	323
Figure 74.12-2 – Coatings: Dimensionally stable carbon-carbon – Potential materials	324
Figure 74.12-3 – Coatings: Dimensionally stable carbon-carbon – Manufacturing method.....	326
Figure 75.3-1 – Elastomers: Schematic of crosslinked rubber molecular network.....	333
Figure 75.3-2 – Elastomers: Typical tensile strength at 23°	336

Figure 75.3-3 – Elastomers: Typical tensile strength at 100°C.....	337
Figure 75.3-4 – Elastomers: Viscoelasticity – hysteresis effect.....	340
Figure 75.3-5 – Elastomers: Creep of a weighted rubber strip.....	346
Figure 75.3-6 – Elastomers: Creep of a weighted rubber strip (logarithmic time).....	346
Figure 75.3-7 – Elastomers: Effect of sample thickness on oxidation rate at 110°C.....	347
Figure 75.3-8 – Elastomers: Arrhenius plot example.....	350
Figure 75.3-9 – Elastomers: Simple rubber block in shear.....	351
Figure 75.3-10 – Elastomers: Increasing compression stiffness by lamination.....	353
Figure 75.3-11 – Elastomers: Elastomeric torsion disc.....	354
Figure 75.4-1 - Metal seals: 'C' profile and serpentine.....	358
Figure 75.5-1 - NASP: Ceramic wafer seal.....	359
Figure 75.5-2 - NASP: Braided rope seal.....	360
Figure 76.7-1 - Integrity control for high-temperature applications: Study logic.....	372
Figure 76.7-2 - Integrity control for high temperature applications: Approach.....	372
Figure 78.2-1 - Whisker and particle reinforced MMC: Fatigue response.....	390
Figure 78.4-1 - MMC potential failure mechanisms under cyclic loading.....	391
Figure 78.4-2 - Failure modes of MMC.....	392
Figure 78.4-3 - MMC: Fatigue response showing matrix failure.....	393
Figure 81.5-1 - Coupon testing: Scanning laser extensometry system.....	412
Figure 81.6-1 - CMC high temperature tensile testing: CEN recommended sample types.....	415

Tables

Table 64.3-1 - Modulus mismatch in composites: Examples.....	30
Table 64.3-2 - CTE mismatch in composites: Examples.....	31
Table 65.1-1 - Particulate reinforced MMCs.....	40
Table 66.1-1 - Fibre reinforced MMC.....	52
Table 66.3-1 - Ti/SiC MMC: Calculated stresses.....	55
Table 67.1-1 - Inorganic/ceramic matrix composites.....	58
Table 69.9-1 – Summary of high temperature materials technologies: Flight-vehicle dependent.....	89
Table 69.9-2 – Summary of high temperature materials technologies: Non-flight vehicle dependent.....	92
Table 69.9-3 – Summary of high temperature materials technologies: European expertise.....	94
Table 70.23-1 – X-38 body flap: Mechanical fasteners – properties.....	142
Table 71.1-1 - TPS: Summary of candidate characteristics.....	163
Table 71.1-2 - TPS and Thermo-structural designs: Material classes.....	164
Table 71.3-1 – Early re-entry capsules: TPS mass fractions.....	168

Table 71.4-1 – Ablative TPS: ALS051 properties.....	173
Table 71.5-1 - Orbiter: TPS material temperature limits.....	176
Table 71.5-2 - TPS: RSI Typical Properties.....	177
Table 71.7-1 – Aerotiss® 2.5D coated carbon-carbon: Properties.....	183
Table 71.7-2 – CMC carbon-silicon carbide: Various TPS programmes and applications.....	184
Table 71.7-3 – CMC TPS: MAN carbon-silicon carbide - Properties.....	185
Table 71.10-1 - TPS: IMI material candidates for different applications.....	191
Table 71.10-2 – TPS: Summary - IMI characterisation test results.....	194
Table 71.11-1 - TPS: Mechanical loads and sources on FEI components.....	196
Table 71.11-2 – FEI-TPS product range.....	197
Table 71.11-3 – TPS: FEI nominal flutter test envelopes.....	200
Table 71.11-4 – FEI-TPS: Summary of verified performances.....	202
Table 71.12-1 – Hermes TPS REI-shingle mass breakdown.....	207
Table 71.12-2 – TETRA/X-38 TPS: C-SiC panel qualification test matrix.....	208
Table 71.12-3 - TETRA/X-38 TPS: Shingle qualification test matrix.....	209
Table 71.12-4 - SPFI: Thermal property evaluation.....	218
Table 71.17-1 – CHA: Subcomponents mass breakdown.....	235
Table 71.17-2 - SEPCARB-INOX 272-01: Properties.....	236
Table 71.17-3 – CHA: Functional test matrix.....	237
Table 71.17-4 – ALSCAP: Thermo-physical data for C/SiC.....	243
Table 71.18-1 - Aeroshell demonstrator: Predicted and actual temperatures.....	247
Table 71.19-1 – Cryogenic insulation: Technical considerations for LH tank concepts.....	253
Table 71.22-1 - Cryogenic insulation: Polymer foam candidate materials.....	257
Table 71.22-2 - Cryogenic insulation: Polymer foam mechanical properties.....	259
Table 71.22-3 – Cryogenic insulation: Ranking criteria and values.....	260
Table 71.23-1 - TPS: HTI development tests for X-38 nose cap assembly.....	264
Table 71.23-2 - TPS: HTI candidate materials.....	266
Table 71.23-3 - TPS: HTI thermal stability test results.....	267
Table 72.4-1 - Titanium alloys: Superplastic characteristics.....	284
Table 75.3-1 – Elastomers: Typical glass transition temperatures.....	334
Table 75.3-2 – Elastomers: Summary of common materials and characteristics.....	336
Table 76.6-1 - Integrity control parameters for new materials.....	371
Table 77.3-1 - MMC: Typical material defects.....	381
Table 77.4-1 - CMC: Typical material defects.....	382
Table 77.5-1 - Coating materials: Typical defects.....	383
Table 77.6-1 - Fusion joints: Example of techniques and use.....	384
Table 77.6-2 - Fused joints: Defects.....	384

Table 77.7-1 - Defects in composite materials after further processing.....	385
Table 77.8-1 - Typical in-service defects	386
Table 78.2-1 - MMC: Effect of particle size on fatigue and fracture toughness	390
Table 78.6-1 - Coatings: Damage tolerance aspects	394
Table 80.3-1 - NDI techniques for MMCs	400
Table 80.4-1 - NDI techniques for defect detection and measurement of C-C and CMC materials	401
Table 80.4-2 - Technical and economical aspects of NDI techniques	402
Table 80.5-1 - Coatings: Inspection techniques	403
Table 80.7-1 - Fused joints: Inspection techniques	404
Table 80.7-2 - Standards for inspection of welded tubes	405
Table 81.9-1 - Test methods: CEN standards for advanced technical ceramic composites	420
Table 81.9-2 - Test methods: CEN standards for advanced technical ceramics - monolithic	421
Table 81.9-3 - Test methods: CEN standards for advanced technical ceramics - coatings	422
Table 81.9-4 - Test methods: CEN standards for advanced technical ceramics – others	422

European Foreword

This document (CEN/TR 17603-32-06:2022) 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 16603-10-02.

This Technical report (CEN/TR 17603-32-06:2022) originates from ECSS-E-HB-32-20 Part 6A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN 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).

Introduction

The Structural materials handbook is published in 8 Parts.

A glossary of terms, definitions and abbreviated terms for these handbooks is contained in Part 8.

The parts are as follows:

TR 17603-32-01	Part 1	Overview and material properties and applications	Clauses 1 - 9
TR 17603-32-02	Part 2	Design calculation methods and general design aspects	Clauses 10 - 22
TR 17603-32-03	Part 3	Load transfer and design of joints and design of structures	Clauses 23 - 32
TR 17603-32-04	Part 4	Integrity control, verification guidelines and manufacturing	Clauses 33 - 45
TR 17603-32-05	Part 5	New advanced materials, advanced metallic materials, general design aspects and load transfer and design of joints	Clauses 46 - 63
TR 17603-32-06	Part 6	Fracture and material modelling, case studies and design and integrity control and inspection	Clauses 64 - 81
TR 17603-32-07	Part 7	Thermal and environmental integrity, manufacturing aspects, in-orbit and health monitoring, soft materials, hybrid materials and nanotechnologies	Clauses 82 - 107
TR 17603-32-08	Part 8	Glossary	