

TNI	Kozmická technika Príručka o konštrukčných materiáloch Časť 2: Metódy výpočtu konštrukčného riešenia a všeobecné konštrukčné aspekty	TNI CEN/TR 17603-32-02 31 0540
------------	---	--

Space engineering - Structural materials handbook - Part 2: Design calculation methods and general design aspects

Táto technická normalizačná informácia obsahuje anglickú verziu CEN/TR 17603-32-02:2022.
This Technical standard information includes the English version of CEN/TR 17603-32-02:2022.

Táto technická normalizačná informácia bola oznámená vo Vestníku ÚNMS SR č. 04/22

TECHNICAL REPORT**CEN/TR 17603-32-02****RAPPORT TECHNIQUE****TECHNISCHER BERICHT**

January 2022

ICS 49.140

English version

**Space engineering - Structural materials handbook - Part
2: Design calculation methods and general design aspects**

Ingénierie spatiale - Manuel des matériaux structuraux
- Partie 2 : Méthodes de calculs de conception et
aspects généraux de conception

Raumfahrttechnik - Handbuch
Konstruktionswerkstoffe - Teil 2:
Konstruktionsberechnungsverfahren und allgemeine
Konstruktionsaspekte

This Technical Report was approved by CEN on 22 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 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.....	25
Introduction.....	26
10 Stress-strain relationships	27
10.1 Introduction	27
10.2 Elastic property prediction for UD ply from constituent properties.....	27
10.3 Analytical notation for elastic constant methods	29
10.4 Calculation methods for elastic constants of UD ply	29
10.5 Longitudinal modulus	31
10.6 Longitudinal Poisson's ratio.....	33
10.7 Transverse modulus.....	34
10.7.1 General.....	34
10.7.2 Jones method	34
10.7.3 Förster/Knappe method	34
10.7.4 Schneider method	35
10.7.5 Puck method.....	35
10.7.6 Tsai method	35
10.7.7 HSB method.....	36
10.7.8 Graphs	36
10.8 Transverse Poisson's ratio	39
10.9 Transverse shear modulus.....	39
10.9.1 General.....	39
10.9.2 Jones method	39
10.9.3 Förster/Knappe method	39
10.9.4 Schneider method	39
10.9.5 Puck method.....	40
10.9.6 Tsai method	40
10.9.7 HSB method.....	40
10.9.8 Graphs	41
10.10 In-plane stress calculation methods	43
10.11 Analytical notation for in-plane methods.....	43

CEN/TR 17603-32-02:2022 (E)

10.12	Stress-strain relations for unidirectional plies	45
10.12.1	Fibre-oriented co-ordinate system.....	45
10.13	On axis stress strain relations	45
10.13.1	General.....	45
10.13.2	Compliance matrix	46
10.13.3	Modulus matrix.....	46
10.13.4	Symmetry of compliance and modulus matrices	46
10.14	Stress-strain relations for a ply of arbitrary orientation.....	46
10.14.1	General.....	46
10.14.2	Off axis stiffness of a unidirectional ply.....	48
10.15	Stiffness matrix for a laminate	49
10.15.1	General laminates.....	49
10.15.2	Symmetric laminates.....	51
10.15.3	Flow chart	52
10.16	Calculation methods with interlaminar stresses and strains.....	53
10.16.1	Calculation with free-edge stresses.....	53
10.17	Qualitative evaluation of interlaminar strength for design purposes.....	55
10.17.1	General.....	55
10.17.2	Variation of fibre direction within a $[\pm\phi^\circ, 0^\circ, \pm\phi^\circ]$ laminate.....	57
10.17.3	Variation of the thickness of the 0° layer within the $[\pm 30^\circ, 0^\circ, \pm 30^\circ]$ laminate	57
10.17.4	Variation of the sequence of layers	58
10.18	References	58
10.18.1	General.....	58
11	Strength prediction and failure criteria.....	60
11.1	Introduction	60
11.1.1	Micro-mechanical strength models.....	60
11.1.2	Lamina failure models	60
11.1.3	Failure criteria studies	61
11.1.4	Summary of World Wide Failure Exercise (WWFE).....	62
11.2	Tensile strength of UD composites in fibre direction.....	64
11.2.1	General.....	64
11.2.2	Weakest-link failure model	64
11.2.3	Cumulative weakening failure model	64
11.2.4	Fibre break propagation model	66
11.2.5	Cumulative group mode failure model.....	66
11.2.6	Status of models	66

CEN/TR 17603-32-02:2022 (E)

11.3	Compressive strength of UD composites in fibre direction.....	66
11.3.1	General.....	66
11.3.2	Extension mode buckling.....	67
11.3.3	Shear mode buckling.....	67
11.3.4	Analysis of compression failure.....	68
11.4	Transverse tensile strength of UD composites.....	70
11.4.1	General.....	70
11.4.2	Prediction of transverse tensile strength.....	71
11.4.3	Empirical analysis.....	71
11.5	Static strength criteria for composites.....	72
11.6	Analytical notation for static strength criteria for composites.....	72
11.6.1	Co-ordinate system.....	72
11.6.2	Formulae.....	73
11.7	Different types of failure criteria.....	74
11.7.1	General.....	74
11.7.2	Evaluation studies.....	75
11.8	Overview - Failure criteria.....	75
11.8.1	Introduction.....	75
11.8.2	Independent conditions.....	76
11.8.3	Interactive conditions – Pure interpolative conditions.....	77
11.8.4	Interactive conditions - Physical considerations.....	78
11.9	Comparison between test data and various failure criteria.....	87
11.9.1	Effects on failure mode.....	87
11.10	Description of failure modes.....	91
11.10.1	Laminates.....	91
11.10.2	Failure.....	91
11.11	Fatigue strength of composites.....	96
11.11.1	Background.....	96
11.11.2	Analytical notation.....	97
11.11.3	Approximation of fatigue life.....	97
11.12	References.....	99
11.12.1	General.....	99
12	Calculation of thermal stress and displacement.....	103
12.1	Introduction.....	103
12.1.1	General.....	103
12.1.2	Longitudinal CTE.....	103
12.1.3	Transverse CTE.....	103

CEN/TR 17603-32-02:2022 (E)

12.2	Analytical notation for thermal stress calculations	104
12.3	Calculation of CTE from constituents	105
12.3.1	CTE in fibre direction.....	105
12.3.2	CTE perpendicular to fibre direction	105
12.4	CTE for a laminate	106
12.5	Thermal stresses within laminate layers.....	108
12.5.1	General.....	108
12.5.2	Residual curing stresses	108
12.6	Stress strain temperature relation	109
12.6.1	General.....	109
12.6.2	Mechanical strains	109
12.6.3	Incremental strain theory.....	109
12.7	Microstress analysis.....	111
12.7.1	General.....	111
12.7.2	Microstresses on fibre axis.....	111
12.7.3	Microstresses normal to fibre axis	111
12.8	References	111
12.8.1	General.....	111
13	Moisture effects on composite properties	113
13.1	Introduction	113
13.1.1	General.....	113
13.1.2	Moisture penetration	113
13.1.3	Moisture effects.....	113
13.2	Analytical notation for moisture effects.....	114
13.3	Typical effects of moisture.....	115
13.3.1	General.....	115
13.3.2	Sample data: Effects of moisture.....	115
13.4	Approximate method for calculation of strength and modulus retention of [0°/90°] laminates.....	120
13.4.1	General.....	120
13.4.2	Modulus retention	120
13.4.3	Strength retention	122
13.5	Moisture content	123
13.5.1	Fick's law	123
13.5.2	Determination of moisture content.....	124
13.5.3	Maximum moisture content	125
13.5.4	Experimental determination of the diffusion coefficient.....	126

CEN/TR 17603-32-02:2022 (E)

13.6	Calculation of swelling coefficient from constituents	128
13.6.1	General	128
13.6.2	Swelling coefficient β_1 in fibre direction.....	128
13.6.3	Swelling coefficient β_2 transverse to fibres	128
13.6.4	Swelling coefficient for a laminate	129
13.7	Coefficient of moisture expansion (CME)	131
13.7.1	Resin behaviour	131
13.7.2	Composite behaviour	132
13.8	References	133
13.8.1	General.....	133
14	Stress concentrations and fracture	135
14.1	Introduction	135
14.1.1	General.....	135
14.1.2	Fracture mechanics models	135
14.2	Analytical notation for stress concentrations	136
14.3	Summary of fracture models	136
14.4	Evaluation of fracture models.....	137
14.5	WEK fracture model.....	138
14.5.1	General.....	138
14.5.2	Circular holes.....	138
14.5.3	Straight crack.....	141
14.6	WN fracture model	144
14.6.1	General.....	144
14.6.2	Failure criteria	144
14.6.3	Characteristics of WN fracture model.....	146
14.6.4	Circular holes.....	147
14.6.5	Straight cracks	151
14.6.6	Point stress criteria.....	152
14.6.7	Average stress criterion	153
14.7	Finite plate models.....	157
14.8	Finite width correction (FWC).....	157
14.8.1	General.....	157
14.8.2	Circular holes.....	159
14.8.3	Centre crack.....	160
14.9	Calculated stress concentration factor at circular holes.....	160
14.9.1	NASA results.....	160
14.9.2	Finite width correction (FWC).....	162

CEN/TR 17603-32-02:2022 (E)

14.9.3	MBB/ERNO study	162
14.10	Stress distribution around circular holes.....	167
14.10.1	General.....	167
14.10.2	Stress concentration due to tensile load.....	167
14.10.3	Stress concentration due to shear load	168
14.11	Interlaminar fracture mechanics	170
14.11.1	Nomenclature.....	170
14.11.2	Delamination and fracture mechanics overview	170
14.11.3	Standard test methods (static and fatigue)	174
14.11.4	Calculation of strain energy release rate in structural analysis	178
14.12	References	184
14.12.1	General.....	184
15	Prediction of dynamic characteristics	188
15.1	Introduction	188
15.2	Definition of damping terms.....	188
15.2.1	General terms	188
15.2.2	Complex modulus model.....	190
15.3	Prediction methods for damping.....	191
15.4	Determination of damping characteristics.....	192
15.4.1	Unidirectional characteristics.....	192
15.4.2	Off axis characteristics	192
15.4.3	Laminate characteristics.....	193
15.5	Approximate data on damping	193
15.6	References	194
15.6.1	General.....	194
16	Computer analysis of composites	195
16.1	Introduction	195
16.2	Computer programs: Analysis of composites	195
16.2.1	General.....	195
16.2.2	Finite element programs.....	197
16.2.3	Laminate analysis programs	198
16.2.4	Special applications programs	200
16.3	ESDU data for composite analysis	202
16.3.1	General.....	202
16.3.2	ESDU data items	202
16.3.3	ESDUpac.....	204
16.4	Buckling of orthotropic plates	204

CEN/TR 17603-32-02:2022 (E)

16.4.1	Title	204
16.4.2	Usage and scope	204
16.4.3	Analysis	204
16.4.4	ESDUpac A7303	204
16.4.5	Notes	205
16.5	Flexural stiffness of flat strips	205
16.5.1	Title	205
16.5.2	Usage and scope	205
16.5.3	Analysis	205
16.6	Metallic skin stiffeners reinforced by composite - local buckling	206
16.6.1	Title	206
16.6.2	Usage and scope	206
16.6.3	Analysis and data	206
16.7	Laminate stress analysis	207
16.7.1	Title	207
16.7.2	Usage and scope	207
16.7.3	Analysis	207
16.8	Plate stiffnesses (In-plane)	208
16.8.1	Title	208
16.8.2	Usage and scope	208
16.8.3	Analysis and methods	208
16.9	Bonded joints - 1	209
16.9.1	Title	209
16.9.2	Usage and scope	209
16.9.3	Analysis and data	209
16.10	Bonded joints - 2	210
16.10.1	Title	210
16.10.2	Usage and scope	210
16.10.3	Analysis and data	210
16.10.4	ESDUpac A7916	211
16.11	Bonded joints - 3	211
16.11.1	Title	211
16.11.2	Usage and scope	211
16.11.3	Analysis and data	212
16.12	Buckling of rectangular specially orthotropic plates	212
16.12.1	Title	212
16.12.2	Usage and scope	212

CEN/TR 17603-32-02:2022 (E)

16.12.3	Analysis and data.....	212
16.13	Bonded joints - 4.....	213
16.13.1	Title.....	213
16.13.2	Usage and scope.....	213
16.13.3	Analysis and data.....	213
16.13.4	ESDUpac A8039.....	214
16.14	Bonded joints - 5.....	214
16.14.1	Title.....	214
16.14.2	Usage and scope.....	214
16.14.3	Information and guidance.....	214
16.15	Buckling of orthotropic plates.....	215
16.15.1	Title.....	215
16.15.2	Usage and scope.....	215
16.15.3	Analysis and data.....	215
16.15.4	ESDUpac A8147.....	215
16.16	Lay-up arrangements for special orthotropy.....	216
16.16.1	Title.....	216
16.16.2	Usage and scope.....	216
16.16.3	Analysis and data.....	216
16.17	Failure modes of laminated composites.....	217
16.17.1	Title.....	217
16.17.2	Usage and scope.....	217
16.17.3	Analysis and failure modes.....	217
16.18	Failure criteria for layers of a laminated composite.....	218
16.18.1	Title.....	218
16.18.2	Usage and scope.....	218
16.18.3	Analysis and data.....	218
16.19	Plate stiffnesses and apparent elastic properties.....	218
16.19.1	Title.....	218
16.19.2	Usage and scope.....	218
16.19.3	Analysis for stiffnesses and elastic properties.....	219
16.19.4	ESDUpac A8335.....	219
16.20	Natural frequencies of laminated flat plates.....	219
16.20.1	Title.....	219
16.20.2	Usage and scope.....	220
16.20.3	Calculation of natural frequencies.....	220
16.20.4	ESDUpac A8336.....	220

CEN/TR 17603-32-02:2022 (E)

16.21	Strain in skin panels under acoustic loading.....	221
16.21.1	Title.....	221
16.21.2	Usage and scope.....	221
16.21.3	Calculation of surface strains.....	221
16.21.4	ESDUpac A8408.....	221
16.22	Failure analysis.....	222
16.22.1	Title.....	222
16.22.2	Usage and scope.....	222
16.22.3	Analysis.....	222
16.22.4	ESDUpac A8418.....	223
16.23	Endurance under acoustic loading.....	224
16.23.1	Title.....	224
16.23.2	Usage and scope.....	224
16.24	Stress and strain around circular holes.....	224
16.24.1	Title.....	224
16.24.2	Usage and scope.....	225
16.24.3	Analysis.....	225
16.24.4	ESDUpac A8501.....	225
16.25	Damping in composite plates.....	226
16.25.1	Title.....	226
16.25.2	Usage and scope.....	226
16.25.3	Calculation of damping.....	226
16.25.4	ESDUpac 8512.....	226
16.26	Sandwich panel natural frequencies.....	227
16.26.1	Title.....	227
16.26.2	Usage and scope.....	227
16.26.3	Calculation of natural frequencies.....	227
16.26.4	ESDUpac A8537.....	228
16.27	Selection of reinforcement around circular holes.....	228
16.28	Buckling of unbalanced composite plates.....	229
16.28.1	Title.....	229
16.28.2	Usage and scope.....	229
16.28.3	Analysis and data.....	229
16.28.4	ESDUpac A8620.....	230
16.29	Sandwich panel response to acoustic loading.....	230
16.29.1	Title.....	230
16.29.2	Usage and scope.....	230

CEN/TR 17603-32-02:2022 (E)

16.29.3	Calculation of natural frequencies and surface strains	231
16.29.4	ESDUpac A8624	231
16.30	Sandwich column and beam face plate wrinkling	231
16.30.1	Title	231
16.30.2	Usage and scope	231
16.30.3	Analysis	232
16.30.4	ESDUpac A8713	232
16.31	Buckling of curved composite panels	233
16.31.1	Title	233
16.31.2	Usage and scope	233
16.31.3	Analysis and data	233
16.31.4	ESDUpac A8725	233
16.32	Sandwich panel face plate wrinkling	234
16.32.1	Title	234
16.32.2	Usage and scope	234
16.32.3	Analysis	234
16.32.4	ESDUpac A8815	235
16.33	Vibration of singly-curved laminated plates	235
16.33.1	Title	235
16.33.2	Usage and scope	235
16.33.3	Calculation of natural frequencies	236
16.33.4	ESDUpac A8911	236
16.34	Plate through-the-thickness shear stiffnesses	236
16.34.1	Title	236
16.34.2	Usage and scope	237
16.34.3	Analysis	237
16.34.4	ESDUpac A8913	237
16.34.5	Notes	237
16.35	Vibration of plates with in-plane loading	238
16.35.1	Title	238
16.35.2	Usage and scope	238
16.35.3	Calculation of natural frequencies	238
16.35.4	ESDUpac A9016	238
16.36	Delamination and free edge stresses	239
16.36.1	Title	239
16.36.2	Usage and scope	239
16.36.3	Analysis	239

CEN/TR 17603-32-02:2022 (E)

16.36.4	ESDUpac A9021	240
16.36.5	Notes	240
16.37	Delamination at termination of plies	240
16.37.1	Title	240
16.37.2	Usage and scope	241
16.37.3	Analysis	241
16.37.4	ESDUpac A9103	241
16.38	Thickness selection to meet a loading combination	242
16.38.1	Title	242
16.38.2	Usage and scope	242
16.38.3	Analysis	242
16.38.4	ESDUpac A9233	242
16.39	ESAComp	243
17	Composite adequate design	244
17.1	Introduction	244
17.2	Anisotropy of composites	244
17.3	Stress-strain relationships	246
17.3.1	Reinforcing fibres	246
17.3.2	Stress concentrations	246
17.4	Fibre strength and stiffness	248
17.4.1	General	248
17.4.2	High stiffness applications	249
17.5	Basic design rules	250
17.5.1	General	250
17.5.2	Aspects of construction	250
17.5.3	Aspects of laminate lay up	253
17.5.4	Fabrication aspects	256
17.6	First steps in designing a composite	259
17.6.1	General	259
17.6.2	Carpet plots	259
17.6.3	Use of carpet plots	261
17.7	References	262
17.7.1	General	262
18	Curing stresses: Effects and prediction	264
18.1	Introduction	264
18.2	Cure process	264
18.2.1	Composite materials	264

CEN/TR 17603-32-02:2022 (E)

18.2.2	Cure parameters	265
18.3	Analytical notation for residual stress	266
18.4	Residual stresses.....	266
18.4.1	General.....	266
18.4.2	Types of residual stresses.....	266
18.5	Calculation of curing stresses	267
18.5.1	Residual stresses after curing	267
18.6	Reduction of thermal stresses and distortions	268
18.6.1	General.....	268
18.6.2	Stress relieving	270
18.7	References	270
18.7.1	General.....	270
19	Manufacturing faults and service damage	272
19.1	Introduction	272
19.2	Manufacturing defects in composite materials.....	274
19.2.1	General.....	274
19.2.2	Description of manufacturing defects	275
19.2.3	Detection of defects	279
19.3	Service threats for composite structures	279
19.4	Impact behaviour of laminates and sandwich constructions	280
19.4.1	General.....	280
19.4.2	Laminates	281
19.4.3	Sandwich panels.....	284
19.5	Impact behaviour	284
19.5.1	General.....	284
19.5.2	BVID	285
19.5.3	Impact tests.....	286
19.5.4	Compression after impact (CAI)	288
19.6	Detection of defects	288
19.6.1	Damage detection techniques.....	288
19.6.2	Laboratory and production based NDT.....	288
19.6.3	Other techniques.....	288
19.7	References	289
19.7.1	General.....	289
19.7.2	ASTM standards	289
20	Environmental aspects of design	290
20.1	Introduction	290

CEN/TR 17603-32-02:2022 (E)

20.2	Description of environments.....	290
20.2.1	Earth environment.....	290
20.2.2	Space environment.....	291
20.2.3	Composite structures.....	295
20.3	Low earth orbit (LEO).....	296
20.4	Geostationary orbit (GEO).....	297
20.5	Deep space exploration.....	297
20.6	Galvanic corrosion.....	298
20.6.1	General.....	298
20.6.2	Physical basis of galvanic corrosion.....	298
20.6.3	Prevention of galvanic corrosion in space structures.....	300
20.7	Effects of moisture on composites.....	300
20.7.1	General.....	300
20.7.2	Modification of CTE by outgassing.....	300
20.7.3	Low coefficient of moisture expansion (CME) resins.....	301
20.7.4	Hot/wet performance.....	301
20.8	LDEF in LEO.....	302
20.8.1	Mission.....	302
20.8.2	Materials and experiments.....	302
20.8.3	Variations in exposure conditions.....	303
20.8.4	Composite materials aboard LDEF.....	305
20.8.5	LDEF experiments M0003-9/10.....	307
20.8.6	LDEF experiment AO 171.....	309
20.8.7	LDEF experiment AO 180.....	311
20.8.8	Surface characterisation of eroded composites.....	311
20.8.9	Overall conclusions on LDEF.....	312
20.8.10	Non-polymeric composites on LDEF.....	312
20.8.11	Polymer films on LDEF.....	312
20.8.12	Lubricants, adhesives and seals on LDEF.....	312
20.9	Thermal cycling.....	313
20.9.1	Conditions.....	313
20.9.2	Damage mechanisms.....	314
20.10	Vacuum.....	317
20.10.1	Effects of vacuum.....	317
20.11	Radiation.....	318
20.11.1	Radiation spectra.....	318
20.11.2	T300/934 in GEO.....	321

CEN/TR 17603-32-02:2022 (E)

20.12	Damage by combined environmental factors.....	322
20.12.1	General.....	322
20.12.2	P75/930 in GEO.....	322
20.12.3	UHM CFRP in GEO and LEO.....	326
20.12.4	PEI CFRP in LEO and GEO.....	329
20.13	Atomic oxygen.....	331
20.13.1	Effects of atomic oxygen.....	331
20.14	Siloxanes and silicon polymers.....	333
20.14.1	Protection methods against ATOX.....	333
20.14.2	Protection of polymer films.....	334
20.14.3	Protection of composites.....	334
20.15	Protective coatings.....	336
20.15.1	Surface coatings.....	336
20.16	Debris.....	337
20.16.1	Classification of debris.....	337
20.16.2	Damage to LDEF.....	338
20.16.3	Damage to composites.....	338
20.16.4	Damage to aluminium alloys.....	339
20.16.5	Damage to thermal control materials.....	339
20.16.6	Significance of impact events.....	340
20.16.7	Protective shielding.....	340
20.17	References.....	341
20.17.1	General.....	341
20.17.2	ECSS documents.....	345
21	Bonded joints.....	347
21.1	Introduction.....	347
21.2	Adhesives.....	347
21.2.1	General.....	347
21.2.2	Types of adhesives.....	347
21.2.3	Adhesives for joining different materials.....	350
21.3	Design of bonded joints.....	352
21.3.1	Basic considerations.....	352
21.3.2	Basic guidelines.....	352
21.3.3	Failure modes.....	352
21.3.4	Features.....	353
21.4	Joint configuration.....	355
21.4.1	Basic configurations.....	355

CEN/TR 17603-32-02:2022 (E)

21.4.2	Orientation of surface fibres	358
21.5	Environmental factors for bonded joints	359
21.5.1	General	359
21.5.2	Effect of moisture	359
21.5.3	Effect of temperature.....	362
21.5.4	Combined moisture and temperature	362
21.6	Bonding defects	363
21.6.1	General	363
21.6.2	Description of bonding defects	363
21.6.3	Inspection of bonded joints.....	370
21.7	Bonded joint failure modes.....	372
21.7.1	Typical failure modes	372
21.7.2	Loading modes	372
21.8	Calculation of bonded joint strength	373
21.9	Analysis of joint configurations	374
21.9.1	Analytical notation	374
21.9.2	Single lap shear joint.....	374
21.9.3	Double lap shear joint	378
21.9.4	Double-lap shear joint under mechanical and temperature loads	380
21.9.5	Single taper scarf joint.....	388
21.9.6	Double taper scarf joint	389
21.9.7	Stepped lap joint	390
21.10	Bonded joint design curves and test data.....	392
21.10.1	General	392
21.11	Acoustic fatigue of bonded configurations	403
21.12	References	405
21.12.1	General	405
21.12.2	ECSS documents.....	406
22	Mechanically fastened joints	407
22.1	Introduction	407
22.2	Basic considerations for design.....	407
22.2.1	Advantages	407
22.2.2	Disadvantages	407
22.3	Factors affecting design	408
22.3.1	General	408
22.3.2	Material parameters	409
22.3.3	Fastener parameters.....	411

CEN/TR 17603-32-02:2022 (E)

22.3.4	Design parameters.....	411
22.4	Bolted joints	416
22.4.1	Material parameters	416
22.4.2	Fastener parameters.....	416
22.4.3	Design parameters.....	418
22.5	Bolted joint: Analysis	418
22.5.1	General.....	418
22.5.2	Analytical methods.....	418
22.5.3	Stress distribution	418
22.5.4	Failure prediction	421
22.5.5	Experimental data	423
22.6	Riveted joints	427
22.6.1	General.....	427
22.6.2	Installation damage of riveted joints	427
22.6.3	Pull through strength.....	428
22.6.4	Fasteners used in composite structures.....	429
22.7	References	431
22.7.1	General.....	431
22.7.2	ECSS standards	432

Figures

Figure 10.2-1	- Derivation of macro-mechanical properties for the analysis of laminates.....	28
Figure 10.5-1	- Longitudinal modulus (E_1) of glass/epoxy.....	31
Figure 10.5-2	- Longitudinal modulus (E_1) of carbon (HT)/epoxy	32
Figure 10.5-3	- Longitudinal modulus (E_1) of carbon (HM)/epoxy.....	32
Figure 10.5-4	- Longitudinal modulus (E_1) of aramid/epoxy	33
Figure 10.7-1	- Transverse modulus (E_2) of glass/epoxy composites	37
Figure 10.7-2	- Transverse modulus (E_2) of carbon (HT)/epoxy composites	37
Figure 10.7-3	- Transverse modulus (E_2) of carbon (HM)/epoxy composites	38
Figure 10.7-4	- Transverse modulus (E_2) of aramid/epoxy composites.....	38
Figure 10.9-1	- Shear modulus (G_{12}) of glass/epoxy composites	41
Figure 10.9-2	- Shear modulus (G_{12}) of carbon (HT)/epoxy composites	42
Figure 10.9-3	- Shear modulus (G_{12}) of carbon (HM)/epoxy composites.....	42
Figure 10.9-4	- Shear modulus (G_{12}) of aramid/epoxy composites.....	43
Figure 10.12-1	- Definition of the co-ordinate system for the analysis of unidirectional plies.....	45
Figure 10.14-1	- Definition of axes.....	47
Figure 10.14-2	- Transformation of stiffness and compliance matrix	49

CEN/TR 17603-32-02:2022 (E)

Figure 10.15-1 - In plane forces and moments	50
Figure 10.15-2 - Geometry of an n -layered laminate	51
Figure 10.15-3 - Calculation of a laminate	52
Figure 10.16-1 - Uniaxial loading of a composite.....	53
Figure 10.16-2 - Typical decrease of interlaminar stresses with high peaks near the edges	54
Figure 10.17-1 - External load on a composite plate.....	55
Figure 10.17-2 - Determination of the critical fibre direction.....	57
Figure 11.2-1 - Fibre reinforced composite: Tensile failure model	65
Figure 11.3-1 - Buckling modes of fibres under compression	67
Figure 11.3-2 - Comparison of predicted and experimental values of longitudinal compressive strength	69
Figure 11.6-1 - Analytical notation: Co-ordinate system	73
Figure 11.8-1 – Cuntze failure criteria - Schematic diagram of failure modes in transversely-isotropic UD material	83
Figure 11.8-2 – Cuntze failure criteria – Notation and formulae for fabric failure conditions.....	86
Figure 11.8-3 – Comparison between predicted failure curves for C-C/SiC composites with experimental data	87
Figure 11.9-1 - Test results: Effect of thickness variation on static failure	88
Figure 11.9-2 - Test results: Effect of static and dynamic loading	89
Figure 11.9-3 - Comparison: Failure theories applied to static strength result-	90
Figure 12.3-1 - CTE of unidirectional composites	105
Figure 12.3-2 - CTE for T300/914 $0^\circ/\pm 45^\circ/90^\circ$ laminates	106
Figure 13.3-1 - Stress/strain curves of Fibredux 914 (neat resin) for different moisture contents tested at RT	116
Figure 13.3-2 - Swelling strain, transverse (UD laminate).....	117
Figure 13.3-3 - Influence of temperature and time on weight gain.....	117
Figure 13.3-4 - Test results: Moisture absorption versus time	118
Figure 13.3-5 - Transverse tensile strength.....	118
Figure 13.3-6 - Transverse modulus of elasticity.....	119
Figure 13.3-7 - Influence of temperature and moisture on fatigue strength of unidirectional 0° laminates	119
Figure 13.4-1 - Moisture: Comparison of calculated and experimental results of strength and stiffness of $[0^\circ/90^\circ]$ GFRP laminates.....	121
Figure 13.4-2 - Moisture: Comparison of calculated and experimental results of strength and stiffness $[0^\circ/90^\circ]$ CFRP laminates.....	122
Figure 13.5-1 - Notation: Definition of axes.....	123
Figure 13.5-2 - Illustration of change of moisture content with square root of time	126
Figure 13.5-3 - Variation of maximum moisture content with relative humidity for a T300/1034 composite	127
Figure 13.6-1 - Moisture: Coefficient of swelling for unidirectional composites	129

CEN/TR 17603-32-02:2022 (E)

Figure 13.6-2 - Moisture: Definition of swelling coefficient β_2 for orthotropic material (unidirectional laminate).....	130
Figure 13.6-3 - Moisture: Swelling coefficients for T300/914 [0°/±45°/90°]s laminates.....	131
Figure 14.4-1 - Strength ratio versus hole diameter: Crack length for WN fracture model - 'Average stress criterion'.....	138
Figure 14.5-1 - Notation: Infinite isotropic plate with circular hole.....	139
Figure 14.5-2 - Comparison between experiment and prediction by WEK model.....	141
Figure 14.5-3 - Notation: Infinite plate with straight crack.....	142
Figure 14.5-4 - Comparison between experiment and prediction by WEK model.....	143
Figure 14.5-5 - Determination of a_c for various laminates.....	144
Figure 14.6-1 - Notation: Point stress criterion diagram.....	145
Figure 14.6-2 - Notation: Average stress criterion diagram.....	146
Figure 14.6-3 - Notation: Infinite orthotropic plate with circular hole.....	147
Figure 14.6-4 - Comparison between experiments and predictions of WN model.....	149
Figure 14.6-5 - Effects of stacking sequence on notch sensitivity.....	150
Figure 14.6-6 - Effects of fibre angle on notch sensitivity.....	150
Figure 14.6-7 - Infinite orthotropic plate with straight crack.....	151
Figure 14.6-8 - Comparison between experiments and predictions of WN model.....	154
Figure 14.6-9 - Critical stress intensity factor K_Q	154
Figure 14.6-10 - Determination of a_0 for various laminates, applying 'Average stress criterion'.....	155
Figure 14.6-11 - Characteristic dimensions as a function of half crack length.....	156
Figure 14.6-12 - Effect of stacking sequence.....	156
Figure 14.8-1 - Anisotropy factor versus net section reduction for centre cracked angle ply CFRP specimens.....	158
Figure 14.8-2 - Anisotropy factor versus net section reduction for centre cracked CFRP specimens.....	159
Figure 14.9-1 - Stress concentration factor (K_{tn}) for orthotropic CFRP laminates with a circular hole, $2 \leq L/W \leq 10$	161
Figure 14.9-2 - Stress distribution at a hole for 0°/0° laminates.....	163
Figure 14.9-3 - Stress distribution at a hole for ±32.5°/0°/±32.5° laminates.....	164
Figure 14.9-4 - Stress distribution at a hole for laminates.....	165
Figure 14.9-5 - Stress distribution at a hole for laminates.....	166
Figure 14.10-1 - Stress concentration due to tensile load.....	167
Figure 14.10-2 - Stress concentration due to shear load.....	169
Figure 14.11-1 - Fracture modes: opening, shearing, and tearing.....	171
Figure 14.11-2 - Outline of no-damage-growth methodology.....	172
Figure 14.11-3 - Fracture mechanics life prediction methodology.....	174
Figure 14.11-4 - DCB and ENF specimens.....	176

CEN/TR 17603-32-02:2022 (E)

Figure 14.11-5 - Representative $G-N_{onset}$ data	178
Figure 14.11-6 - Node definitions for 2D VCCT	180
Figure 14.11-7 - Node definitions for 3D VCCT	182
Figure 14.11-8 - $G-a$ curve for a stiffener debond	183
Figure 14.11-9 - Schematics of possible $G-a$ curves	183
Figure 15.5-1 - Summary of loss factors for various fibres / epoxy composites	193
Figure 17.2-1 - Anisotropic behaviour of carbon fibre reinforced plastic	245
Figure 17.3-1 - Stress-strain response of CFRP (in tension and compression)	247
Figure 17.3-2 - Fatigue strength of notched and un-notched aluminium and carbon fibre reinforced plastic	248
Figure 17.4-1 - Specific tensile strength and modulus properties of reinforcing fibres	249
Figure 17.5-1 - Shaping changes in thickness	250
Figure 17.5-2 - Design of shapes	251
Figure 17.5-3 - Need for radii on corners	251
Figure 17.5-4 - Cut outs: Bad and good practice	252
Figure 17.5-5 - Directionality of tensile strength of various semi-product forms: Preferred loading direction	254
Figure 17.5-6 - Symmetrical lay-up: Avoids warpage and minimises loading the resin matrix	255
Figure 17.5-7 - Split design technique	255
Figure 17.5-8 - Dimensional change for various materials due to a temperature change of 100°	256
Figure 17.5-9 - Fabrication costs for a CFRP structure	257
Figure 17.5-10 - Comparison of costs: Metallic and CFRP	258
Figure 17.6-1 - Carpet plot curves of modulus for 0°/±45°/90° laminates	260
Figure 17.6-2 - Carpet plot curves of strength for 0°/±45°/90° laminates	260
Figure 18.2-1 - Typical cure cycle for CFRP	265
Figure 18.5-1 - Residual stresses after curing	268
Figure 18.6-1 - Normalised maximum curing stresses in [±θ°]s laminates	269
Figure 18.6-2 - Through thickness tensor polynomial distributions for curing stresses and stresses at first failure in [±θ°]s laminates	270
Figure 19.1-1 - Examples of defects in composite materials	273
Figure 19.4-1 - The primary failure modes of composite laminates under impact loading	282
Figure 19.5-1 - Multiple delaminations in a [(0 ₂ , ±45) ₂]s CFRP laminate caused by drop weight impact	285
Figure 19.5-2 - Impact damage in a 64-ply CFRP laminate caused by high velocity impact	286
Figure 20.2-1 - Space environment effects: Vacuum	292
Figure 20.2-2 - Space environment effects: Radiation	292
Figure 20.2-3 - Space environment effects: Temperature	293
Figure 20.2-4 - Space environment effects: Micrometeoroids and debris	293

CEN/TR 17603-32-02:2022 (E)

Figure 20.2-5 - Space environment effects: Atomic oxygen (ATOX).....	294
Figure 20.2-6 - Space environment effects: Re-entry	294
Figure 20.6-1 - Galvanic corrosion: Potential in 3.5 % NaCl solution	299
Figure 20.8-1 – LDEF: Experiment locations (M0003-10)	305
Figure 20.8-2 - LDEF: Estimated AO erosion depth versus fibre content for various epoxy CFRP materials	307
Figure 20.9-1 - Ratio of residual tensile strength to the initial strength versus number of thermal cycles (-160 to +95°C): [$\pm 45^\circ$] _{2S} specimen tensile tested at RT and 100°C.....	315
Figure 20.9-2 - Degradation of stiffness of various materials due to thermal cycling (-160°C to + 95°C): [$\pm 45^\circ$] _{2S} specimen tensile tested at RT and 100°C.....	316
Figure 20.11-1 - UV radiation: Effects on tensile moduli of carbon/epoxy composites	319
Figure 20.11-2 - Effects of total radiation dose on microcrack formation in composite specimens subjected to 100 thermal cycles (-150°C to +80°C)	320
Figure 20.11-3 - Effects of total radiation dose on the coefficient of thermal expansion of a toughened composite system (-150°C to -73°C).....	321
Figure 20.12-1 - Effect of cure temperature and electron radiation exposure on the T _g of P75/930 in GEO	324
Figure 20.12-2 - Effects of cure temperature and electron radiation exposure on the shear strength of P75/930 in GEO.....	325
Figure 20.12-3 - Step simulation of 7 years in GEO.....	327
Figure 20.12-4 - Effect of ATOX erosion on different CFRP composites.....	329
Figure 20.12-5 - Irradiation and thermal cycling: Changes in mechanical properties for C6000/PEI.....	331
Figure 21.2-1 - Adhesives for bonding different materials.....	351
Figure 21.4-1 - Bonded joints: Basic configurations	357
Figure 21.4-2 - Bonded joints: Orientation of surface fibre.....	358
Figure 21.5-1 - Effect of moisture on stress distributions in adhesive bonded joints	360
Figure 21.5-2 - Influence of moisture absorption/desorption on peak adhesive shear strains	361
Figure 21.5-3 - Effect of progressive moisture absorption on bond strain	362
Figure 21.6-1 - Bonded joints: Examples of acceptable bond flaw sizes.....	364
Figure 21.6-2 - Typical quality zoning for bonded joints.....	365
Figure 21.6-3 - Adhesive shear stresses in bonded joints.....	366
Figure 21.6-4 - Adhesive stresses in flawed bonded joints.....	366
Figure 21.6-5 - Adhesive stresses in flawed bonded joints.....	367
Figure 21.6-6 - Adhesive stresses in flawed bonded joints.....	367
Figure 21.6-7 - Adhesive bonded joints: Effect of debond flaws on flexibility	368
Figure 21.6-8 - Variation of peak induced adhesive stress with thickness of adhesive at ends of overlap	369
Figure 21.7-1 - Components of bonded joint strength.....	372

CEN/TR 17603-32-02:2022 (E)

Figure 21.7-2 - Bonded joints: Loading modes or types of stresses.....	373
Figure 21.9-1 - Analysis: Notation for symmetrical single-lap shear joint	375
Figure 21.9-2 - Analysis: Notation for single-lap joint R -degree peeling.....	376
Figure 21.9-3 - θ -degree peeling strength.....	377
Figure 21.9-4 - Analysis: Notation for double-lap shear joint.....	378
Figure 21.9-5 - Analysis: Notation for double lap joint (standard overlap length)	380
Figure 21.9-6 - Shear stress distribution versus the adhesive length ($E_1t_1 = E_2t_2$) for single lap joint without eccentricity.....	380
Figure 21.9-7 - Stress concentration factor f_2 as a function of K_2 with parameter ω_2	382
Figure 21.9-8 - Shear stress distribution for large overlap lengths	384
Figure 21.9-9 - Stress concentration factor for large overlap lengths	385
Figure 21.9-10 - Shear stress distribution versus the normalised bonding length x/L for a bonded joint between CFRP-HT unidirectional (60 vol. %) and aluminium, titanium, GFRP quasi-isotropic, and GFRP unidirectional materials	386
Figure 21.9-11 - Shear stress distribution versus the normalised bonding length x/L for a bonded joint between CFRP HT quasi isotropic (60 vol. %) and aluminium, titanium, GFRP quasi isotropic, and GFRP unidirectional materials	387
Figure 21.9-12 - Analysis: Notation for single taper scarf joint	388
Figure 21.9-13 - Analysis: Notation for symmetrical double tapered scarf joint	389
Figure 21.9-14 - Analysis: Notation for stepped lap joint (recessed and simple)	390
Figure 21.9-15 - Analysis: Notation for recessed and simple scarf joints (four or more steps)	391
Figure 21.10-1 - Design curve: Single lap shear joint	393
Figure 21.10-2 - Design curve: Single lap shear joint	394
Figure 21.10-3 - Design curve: Single lap shear joint	395
Figure 21.10-4 - Design curve: Lower bond tension single lap shear joint strength versus lap length	395
Figure 21.10-5 - Design curve: Lower bond tension single lap shear joint strength versus lap length	396
Figure 21.10-6 - Design curve: Lower bond tension single lap compression loaded joint strength versus lap length	396
Figure 21.10-7 - Design curve: Single lap tension fatigue S-N curve	397
Figure 21.10-8 - Design curve: Single-lap shear joint tension fatigue S-N curve.....	397
Figure 21.10-9 - Design curve: Double lap shear joint	398
Figure 21.10-10 - Design curve: Symmetrical double scarf joint strength	399
Figure 21.10-11 - Design curve: Symmetrical double scarf joint strength	400
Figure 21.10-12 - Design curve: Symmetrical double scarf joint, tension fatigue S-N curve	401
Figure 21.10-13 - Design curve: Symmetrical double scarf joint tension fatigue S-N curve	402

CEN/TR 17603-32-02:2022 (E)

Figure 21.10-14 - Design curve: Symmetrical double scarf joint tension fatigue S-N curve	403
Figure 21.11-1 - Bonded joint configurations in Hercules AS 4/3501-6	404
Figure 22.3-1 - Bolted joints: Bearing stresses for various CFRP ply configurations	410
Figure 22.3-2 - Mechanically fastened joints: Examples of configurations	411
Figure 22.3-3 - Mechanically fastened joints: Definition of joint geometry	413
Figure 22.3-4 - Bolted joints: Failure modes	415
Figure 22.3-5 - Local reinforcements for bolted joints	416
Figure 22.4-1 - Bearing strength of bolted carbon fibre reinforced laminates	417
Figure 22.5-1 – Stress σ_2 along the x_1 -axis in an isotropic infinite plate containing an unloaded circular hole	419
Figure 22.5-2 - Stress σ_2 along the x_1 -axis in an orthotropic infinite plate $[0^\circ/90^\circ]$ containing an unloaded circular hole	420
Figure 22.5-3 - Stress σ_2 along the x_1 -axis in an isotropic plate of finite width containing a loaded hole	421
Figure 22.5-4 - Whitney/Nuismer failure hypothesis: Characteristic curve	422
Figure 22.5-5 - Bolted joints: Test device and configuration for in- plane face sheet loading	424
Figure 22.5-6 - Bolted joints: Bearing stress at failure point of CFRP facings with different lay-ups.....	426
Figure 22.6-1 - Rivets: Improvement in pull-through strength by larger flush head diameter and footprint	428
Figure 22.6-2 - Types of rivets for aerospace materials	430

Tables

Table 10.4-1 - Elastic property data for comparison	30
Table 10.4-2 - Basis of calculation methods for different authors.....	30
Table 10.17-1 - Intralaminar stresses and strains: κ value for various stacking sequences.....	58
Table 10.17-2 - Intralaminar stresses and strains: κ value at interface for various stacking sequences.....	58
Table 11.10-1 - Failure modes of unidirectional laminates	92
Table 11.10-2 - Failure modes of multidirectional laminates	94
Table 11.10-3 - Examples of some failure modes.....	95
Table 13.5-1 - Summary of constants for the determination of the maximum moisture content, \hat{M}	125
Table 13.7-1 - Moisture absorption: Cyanate ester Fiberite 954 composites.....	132
Table 14.1-1 - Intrinsic and extrinsic variables relevant for stress intensity factors	135
Table 14.3-1 - Some fracture models and their authors	136
Table 14.9-1 - HT carbon/epoxy	160

CEN/TR 17603-32-02:2022 (E)

Table 14.9-2 - K_T^∞ for various laminates, $w/d \rightarrow \infty$	161
Table 14.9-3 - Material data	162
Table 14.11-1 - Standard test methods	176
Table 16.2-1 - Commonly available software for the analysis of composites	195
Table 16.2-2 - Computer programs for finite element analysis.....	197
Table 16.2-3 - Computer programs for laminate analysis	198
Table 16.2-4 - Computer programs for special composite applications.....	200
Table 16.3-1 - ESDU data sheets for composite analysis	203
Table 17.5-1 - Minimum radii for fibres and laminates	252
Table 17.5-2 - Basic and semi-product forms	253
Table 17.5-3 - Composite manufacturing methods	259
Table 19.2-1 - Types of defects in composite materials	275
Table 20.8-1 – LDEF: Polymer composites	304
Table 20.8-2 - LDEF: Exposure levels.....	305
Table 20.8-3 - LDEF: Composite material classifications.....	306
Table 20.8-4 - LDEF experiment AO 171: Tensile properties of composites.....	310
Table 20.9-1 - Coefficient of thermal expansion for $\pm 45^\circ$	314
Table 20.12-1 - Microcrack densities in $[0_2/90_2]_s$ CFRP laminates.....	328
Table 20.12-2 - GEO and LEO effects: Mechanical properties of C6000/PEI composites...	330
Table 20.13-1 - Reaction efficiencies for some selected composite polymers and organic films: Determined by ~40 hours of LEO exposure in space.....	332
Table 20.13-2 - Effects of short-term LEO exposure on coefficient of thermal expansion for T300/934 carbon/epoxy laminates (RT to $+82^\circ\text{C}$).....	333
Table 21.2-1 - Adhesives: Common types.....	348
Table 21.2-2 - Adhesives: Typical characteristics	349
Table 21.6-1 - Bonded joints: Description of NDT methods	370
Table 21.6-2 - Bonded joints: Detection methods for various defects	371
Table 21.10-1 - Bonded joints: Summary of data curves	392
Table 22.5-1 - Bolted joints: Results of static test on material 914C T300.....	425
Table 22.5-2 - Bolted joints: Results of static test on material 914C – HM.....	426
Table 22.6-1 - Types of fasteners used to join aerospace materials	429

European Foreword

This document (CEN/TR 17603-32-02:2022) 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 17603-32-02:2022) originates from ECSS-E-HB-32-20 Part 2A.

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).

CEN/TR 17603-32-02:2022 (E)

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	

koniec náhľadu – text ďalej pokračuje v platenej verzii STN