The Second Generation Eurocodes

Key changes and benefits through design examples

Online, 3-5 June 2025

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CEN/TS 19101:2022, Design of Fibre-Polymer Composite Structures

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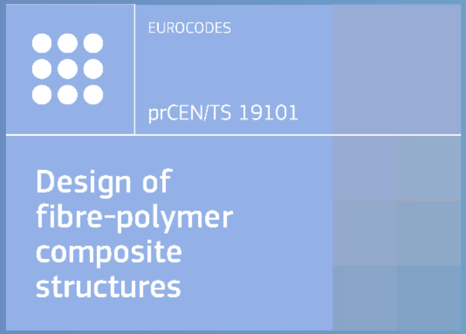


OUTLINE

I. HISTORICAL DEVELOPMENT OF CEN/TS 19101:2022

I.1. Start of the Activity & CEN Procedure

CEN[1] **procedure** to develop a Eurocode includes **three steps**:

1) Publication of a Technical & Scientific Report
2) Publication of a Technical Specification (TS)[2]
3) After a period of trial use and commenting, conversion of TS into Eurocode

[1] European Committee for Standardization

[2] Any conflicting national standards may continue to exist before an Eurocode is available

I.2. STEP 1 – PUBLICATION OF THE SCIENTIFIC & TECHNICAL REPORT

- **Step 1:** 2010 - 2016
- Technical & Scientific Report subjected to a Formal Vote: approved, with the request to develop in further depth the following topics:
  - Basis of design (partial factors, conversion factors, creep coefficients)
  - ULS of sandwich panels
  - Creep rupture
  - Fatigue
  - Detailing
  - Adhesive joints
  - Fire design

I.3. STEP 2 – DRAFTING OF THE TECHNICAL SPECIFICATION

- **Step 2:** 2018 - 2022
- Appointment of Project Team WG.T2 (07/2018 – 04/2021):
  - João Ramôa Correia (IST, ULisboa, Portugal)
  - Thomas Keller (EPFL, Switzerland)
  - Jan Knippers (University of Stuttgart, Germany)
  - Toby Mottram (University of Warwick, UK)
  - Carlo Paulotto (Acciona/Ferrovial, Spain)
  - Till Vallée (Fraunhofer Institute, Germany, until 11/2019)
  - José Sena-Cruz (University of Minho, Portugal, since 09/2020)

Close collaboration with Working Group WG4 of CEN TC250
Convenor: Luigi Ascione (University of Salerno, Italy)

I.3. Step 2 – Drafting of the Technical Specification

- **Step 2:** 2018 - 2022
- **Project Team WG.T2 - roadmap:**

1) Develop **Technical Specification (TS)**, as per CEN's mandate, by:
   - adopting CEN's policy guidelines and procedures (formatting, verbal forms, etc.)
   - taking into account/replying to NSB comments not incorporated in previous stage
   - revising aspects identified to require major improvements
2) Develop **Background Document (BD)** alongside the TS, by:
   - Adding further information whenever applicable/needed
   - Introducing and adequately citing all necessary references that allow tracing the options and sources of the content of the TS, highlighting research needs
3) Develop collection of **Worked Examples (WE)**, for typical design cases

Drafting Team + Review Panel (WG4, other experts) for all documents

I.3. STEP 2 – DRAFTING OF THE TECHNICAL SPECIFICATION

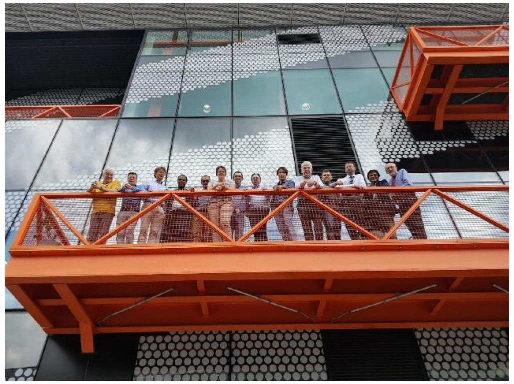
- **Step 2:** 2018 - 2022
- **Methodology:**

  13 joint WG4/PT plenary meetings (6 face-to-face, 7 web after 02/2020)

  Numerous meetings of smaller work teams (PT/WG4 members)

  Interactions with other SCs and WGs of CEN:

  - Sub-Committee SC10 (EN 1990), Prof. John Dalsgaard Sørensen
  - Horizontal Group (HG) Fire, Prof. Paulo Vila Real
  - Ad-Hoc Horizontal Group (AHG) Fatigue, Prof. Johan Maljaars



I.3. STEP 2 – DRAFTING OF THE TECHNICAL SPECIFICATION

- **Step 2:** 2018 - 2022
- **Milestones:**
  - First draft: 31/1/2020 (125 comments from NSB/reviewers)
  - Second draft: 30/4/2020 (123 comments)
  - Third draft: 30/10/2020 (155 comments)
  - Final draft: 30/4/2021 (75 comments)

4 Informal NSB inquiries
478 comments

  - Consensus of WG4 to proceed to ballot process: 13/7/2021
  - Reviewing (2) by TC250 Technical Reviewer (Mariapia Angelino): 22/9/2021
  - Revised final draft submitted to TC250: 7/10/2021
  - Ballot: 13/11/2021 – decision to proceed to Formal Vote (18y/0n/2a)
  - Formal Vote: 22/7/2022 – approved by unanimity (23y/0n)
  - Publication of TS: 10/2022 (~1 year ahead of swim lane)
  - Publication of BD and WE: 2021 (draft) and 2025 (final)

II. STRUCTURE AND CONTENT OF CEN/TS 19101:2022

STRUCTURE OF CEN/TS 19101

- Type and sequence of main clauses according to common structure of new generation of Eurocodes
- 12 Clauses + 5 Annexes
- 238 pages

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TECHNICAL SPECIFICATION
SPÉCIFICATION TECHNIQUE
TECHNISCHE SPEZIFIKATION

CEN/TS 19101

October 2022

ICS 91.010.30

English Version

Design of fibre-polymer composite structures

Calcul des structures en matériaux composites

Bemessung von Tragwerken aus Faserverbund-Kunststoffen

This Technical Specification (CEN/TS) was approved by CEN on 22 August 2022 for provisional application.

The period of validity of this CEN/TS is limited initially to three years. After two years the members of CEN will be requested to submit their comments, particularly on the question whether the CEN/TS can be converted into a European Standard.

CEN members are required to announce the existence of this CEN/TS in the same way as for an EN and to make the CEN/TS available promptly at national level in an appropriate form. It is permissible to keep conflicting national standards in force (in parallel to the CEN/TS) until the final decision about the possible conversion of the CEN/TS into an EN is reached.

CEN members are the national standards bodies 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, Türkiye and United Kingdom.

EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

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

Ref. No. CEN/TS 19101:2022 E

STRUCTURE OF CEN/TS 19101

1	Scope
2	Normative references
3	Terms, definitions and symbols
4	Basis of design
5	Materials
6	Durability
7	Structural analysis
8	Ultimate limit states
9	Serviceability limit states
10	Fatigue
11	Detailing
12	Connections and joints
A	Creep coefficients (informative)
B	Indicative values of material properties for preliminary design (informative)
C	Buckling of orthotropic laminates and profiles (normative)
D	Structural fire design (normative)
E	Bridge details (informative)

1. Scope

TS applicable to:

Buildings, bridges, other civil engineering structures

Permanent, temporary structures

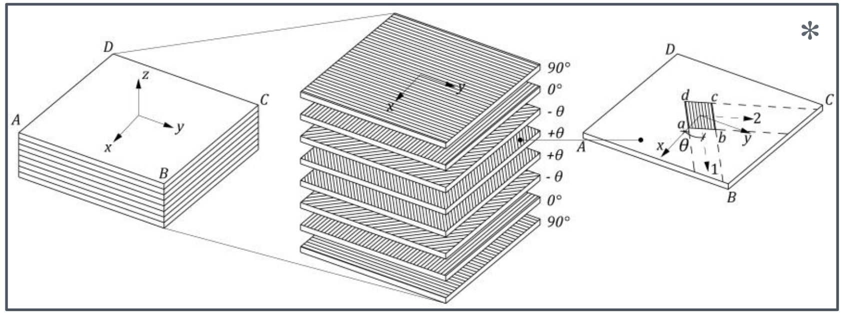
All-composite structures, hybrid-composite structures

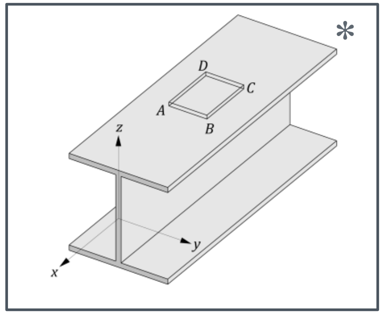
Laminates, profiles, sandwich panels

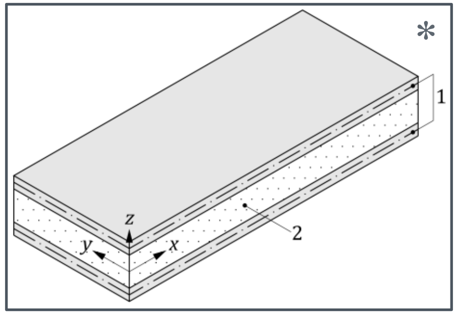
Joints: Bolted, bonded

Constituent materials:

- Glass, carbon, basalt, aramid fibres
- Thermoset resins and adhesives
- Polymeric foam, balsa wood cores







1. Scope

TS does not cover:

Cables, concrete rebars and strengthening systems[1]

Special types of works (e.g. tanks, containers, pressure vessels)

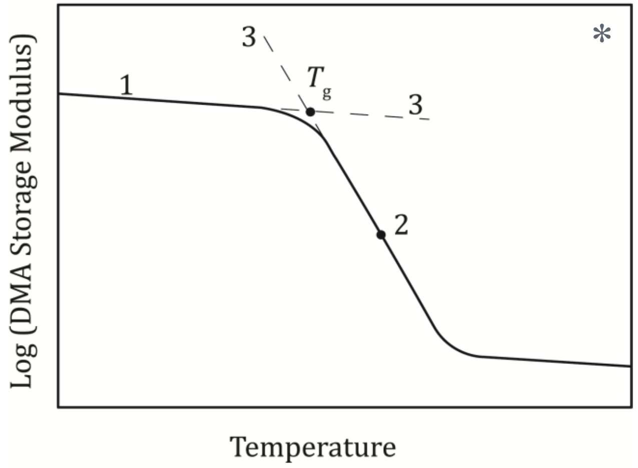
Honeycomb cores

Thermoplastic resins

Material temperature in service conditions, T_s:

-40°C < T_s < T_g[2] - 20°C

$T_g \geq$ 60°C (recommendation)



[1] Addressed in respectively Annexes R and J of new EN 1992-1-1 (Eurocode 2)

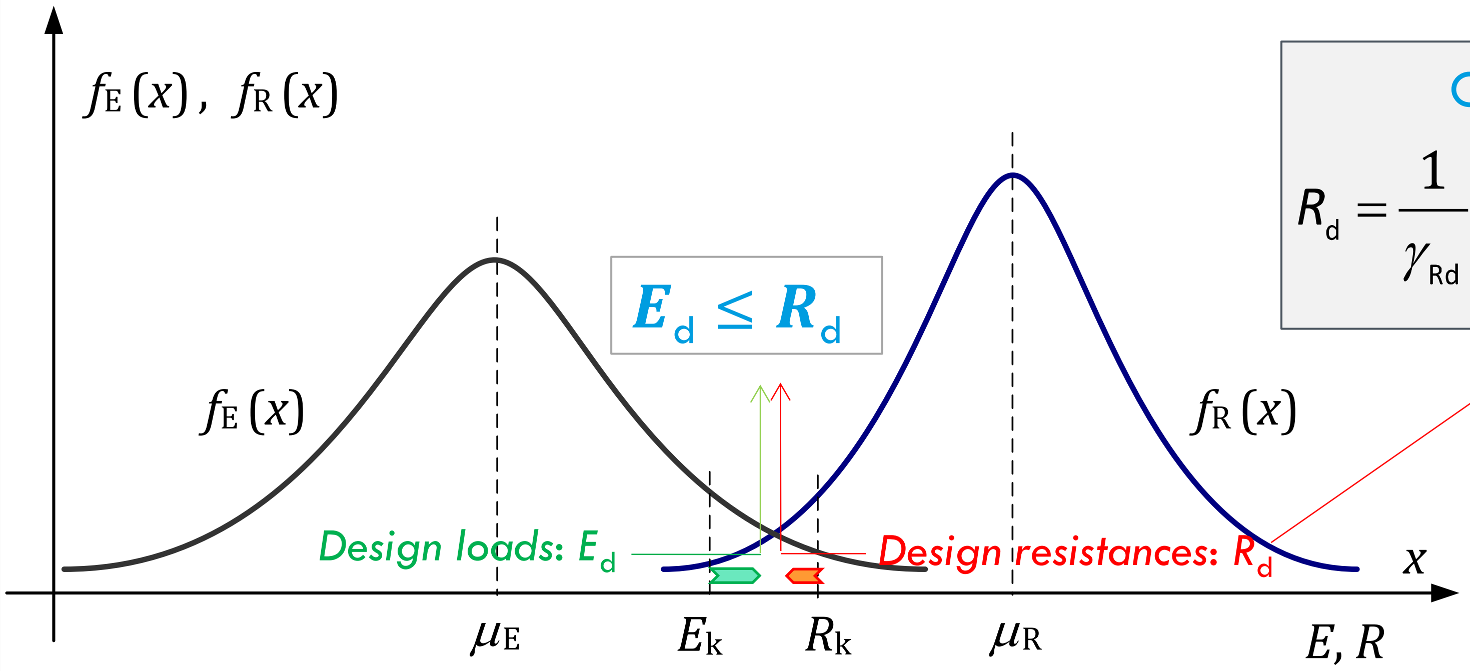
[2] T_g is specified as the onset value of the storage modulus decay, obtained from dynamic mechanical analysis (DMA), and should be at least 60°C (as for ASTM D7028)

4. Basis of Design

Resistance format follows philosophy and partial factor format of EN 1990:

- Semi-probabilistic equation, including partial factors and characteristic values of parameters of design, assures that design complies with target reliability index (β)

- Design value of load effects (E_d) compared with design value of resistance (R_d)



General Format

$$R_d = \frac{1}{\gamma_{Rd}} R\left\{\eta_{c,i} \cdot \frac{X_{k,i}}{\gamma_{m,i}}; a_d; \sum F_{Ed}\right\}$$

4. Basis of Design

Most ULS Verifications of components/members & bolted connections

Design value of resistance (RFA)

$$R_{\mathrm{d}} = \frac{1}{\gamma_{\mathrm{Rd}} \cdot \gamma_{m}} R\{\eta_{\mathrm{c},i} \cdot X_{\mathrm{k},i}; a_{\mathrm{d}}; \sum F_{\mathrm{Ed}}\}$$

- γ_{Rd} - partial factor accounting for uncertainty in resistance model, and geometrical deviations
  (where possible, derived from statistical/reliability analyses)
- γ_{m} - partial factor for a **representative** material or product property
  (determined from the variability [CoV] of that representative material property)
- $R\{\ldots\}$ - output of resistance model
  ("pure" mechanical models, typically without resorting to calibration processes)
- $X_{\mathrm{k},i}$ - characteristic values of material properties (defined as 5% fractiles)
  (determined by testing as per appropriate test standard/statistical methods)
- $\eta_{\mathrm{c},i}$ - conversion factors (effects of temperature, moisture, ageing of materials)
  (defined based on a large-scale review of experimental data)
- i – i^{th} material or product property

4. Basis of Design – Definition of Partial Factor γ_m

- Material properties determined from standard tests on coupons extracted from laminated product
- For a given material property, deviation can differ among different producers
  (different constituent materials, fibre content, layup, manufacturing process)
- γ_m defined based on CoV of experimental data, V_x (EN 1990)
  (from test results of specific producer that supplies material; may be defined from quality control records)

Table 1: Material partial factor g_m as a function of V_x (when V_x is known).

V_x	0,05	0,10	0,15	0,20	0,25	0,30	0,35	0,40	0,45
g_m	1,07	1,15	1,23	1,32	1,41	1,51	1,61	1,71	1,82

For each design case, actual material uncertainty is directly accounted for (influence of different combinations of (i) materials, (ii) production processes or (iii) quality control) – in composites, uncertainty is not bound to a specific range!

4. Basis of Design

Creep Rupture, Fatigue, Adhesive Connections and Fire

Design value of resistance (MFA)

$$R_d = R\left\{\eta_{c,i} \cdot \frac{X_{k,i}}{\gamma_M}; a_d; \sum F_{Ed}\right\}$$

- γ_M - **single partial factor** [within resistance model] accounting for uncertainty in resistance model, unfavourable deviations of relevant material or product properties from their characteristic values and random part of conversion factor, and geometrical deviations, if these are not modelled explicitly

Rationale

- Insufficient knowledge and test data
- Not possible to determine separate partial factors for resistance model (γ_{Rd}) and material uncertainty (γ_m)

4. Basis of Design – Definition of Partial Factor γ_{Rd}

Survey of test data from the literature[1]:

1. Preliminary values of γ_{Rd} defined from design value method, EN 1990 (Annex C)

   Survey of structural test results published to assess resistance to each failure mode

2. Reliability analyses to validate/calibrate the preliminary values of γ_{Rd}

   Different cases of design, representative of civil engineering applications

3. Proposal of partial factors for design by rounding γ_{Rd} values to nearest 0,05

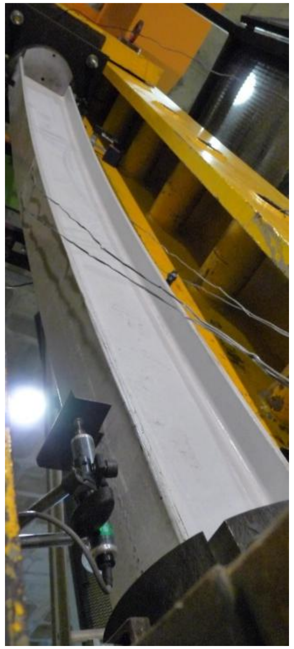
[1] Strict requirements to include results in database: (i) completeness of relevant mechanical properties, (ii) obtained from standardized test procedures; (iii) "clear" failure modes; (iv) peer-reviewed publications

4. Basis of Design – Definition of Partial Factor γ_{Rd}

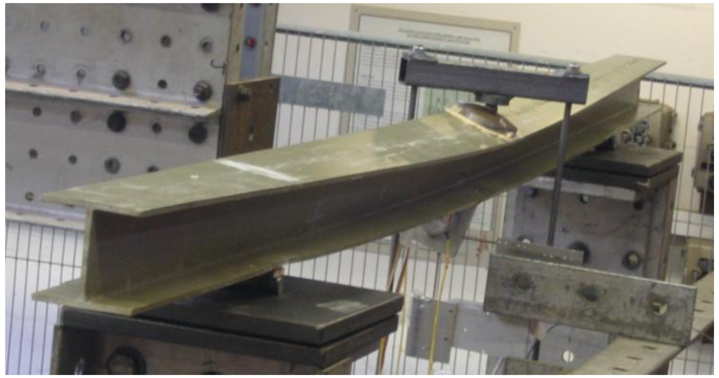
Table 2: Values of g_{Rd} for profiles and laminates.

*

Material failure	Global buckling			Local buckling
	Flexural	Lateral-torsional	Flexural-torsional	
1,40	1,30	1,30	1,55	1,30



Flexural buckling (columns)



LT buckling (beams)

Local buckling

4. Basis of Design – Definition of Partial Factor γ_{Rd}

Table 2: Values of γ_{Rd} for profiles and laminates.

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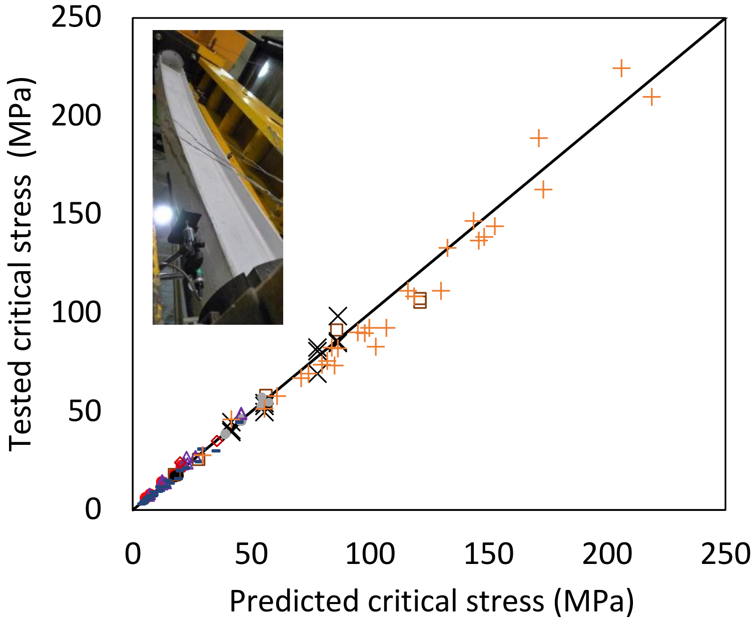
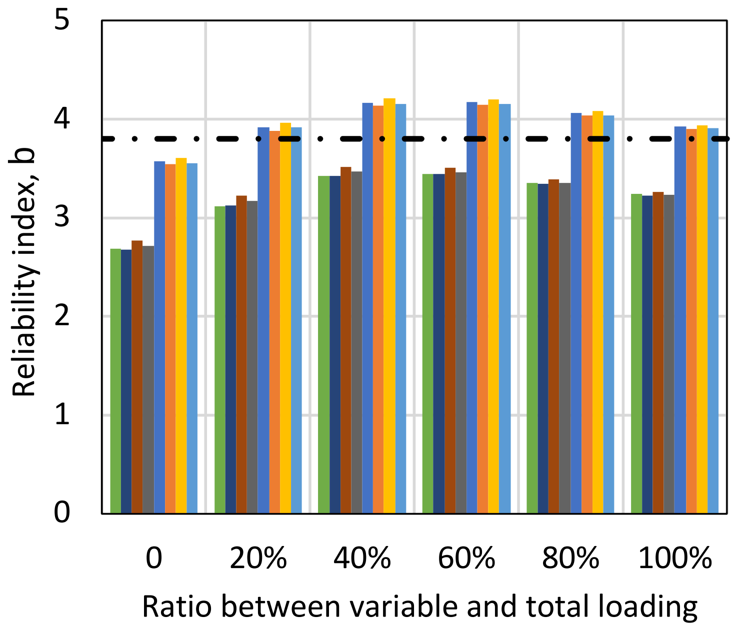


Flexural buckling (columns): assessment of model uncertainties



LT buckling (beams): β (before calibration) for 8 cases of design and 6 load ratios

4. Basis of Design – Definition of Partial Factor γ_M

Design	γ_M	Rationale/source
Creep rupture	1.5	Partial factors for material failure
Fatigue	1.5 to 3.0[1]	Eurocomp, plausibility checks
Adhesive connections	1.5 to 2.5[2]	Eurocomp
Fire	1.0	Fire parts of other Eurocodes

Limited test data available (future validation required)

[1] Depending on: (i) consequences of fatigue failure; (ii) ease of inspection and repair of fatigue sensitive components

[2] Depending on: (i) type of inspection and maintenance and accessibility of adhesive connection; (ii) application conditions

4. Basis of Design – Definition of Conversion Factor η_c

$$\eta_c = \eta_{ct} \cdot \eta_{cm}$$

Conversion factors for temperature (η_{ct}) and moisture (η_{cm}) (values derived from experimental results[1])

Temperature, η_{ct}	Changes of properties due to material temperatures in service conditions (-40°C ≤ T_s ≤ T_g - 20°C) relative to properties at 20°C, excluding effects of long-term exposure[2]
Moisture η_{cm}	Changes of material properties due to moisture absorption over time, including ageing effects resulting from long-term exposure

[1] 2 Criteria: (i) Conservative estimates for most test results (> ~90%)
(ii) Maximum relative differences for overestimated test data (< ~15%)

[2] Long-term exposure to elevated temperatures below T_g usually contributes to increase mechanical properties of polymeric materials due to post-curing effects

4. Basis of Design – Definition of Conversion Factor η_{ct}

Temperature

Survey of test data from the literature – **criteria**:

1. Reference material properties at ambient temperature (~20 °C) determined from experimental tests (standard methods)

2. T_g of FRP material stated, determined by DMA tests (ISO 6721-11), and defined based on the onset value of the storage modulus curve[1]

3. No change in failure modes at elevated temperature, compared to those observed in tests performed at ambient temperature

[1] As it provides a direct relation with the reduction in mechanical properties (in a limited number of cases, some assumptions had to be made in this respect).

4. Basis of Design – Definition of Conversion Factor η_{ct}

22 studies published in the literature, 251 test results (average values, ~1000 tests)

Fibre reinforcement: glass, carbon, basalt

Polymer-matrix: polyester, vinylester, epoxy

Shape: profiles (I, C, tubular), flat plates, bars

Manufacturing: pultrusion, hand layup, vacuum infusion

T_g: 38 to 157 (°C)

Test temperature: -40 to +700 (°C)

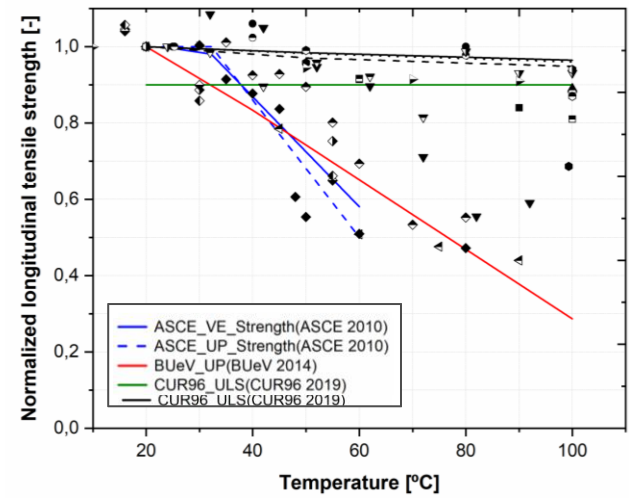
Loading: tension, compression (coupon and full-section), in-plane shear (off-axis tension and Iosipescu) and interlaminar shear

Properties: longitudinal tensile strength, tensile modulus, compressive strength, compressive modulus, in-plane shear strength, in-plane shear modulus, interlaminar shear strength (fibre/matrix dominated)

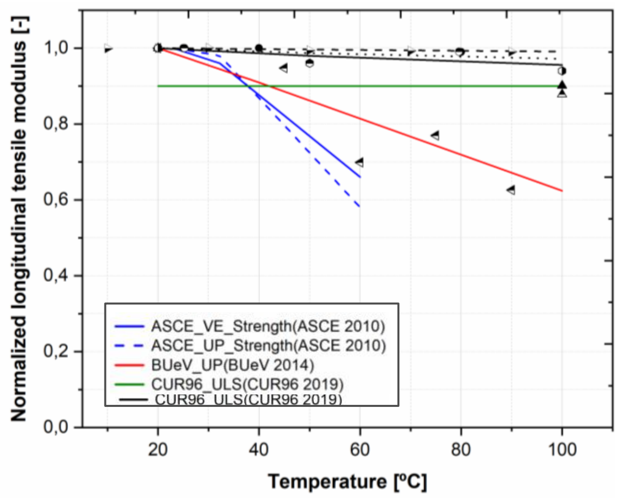
Tensile tests at elevated temperature

4. Basis of Design – Definition of Conversion Factor η_{ct}

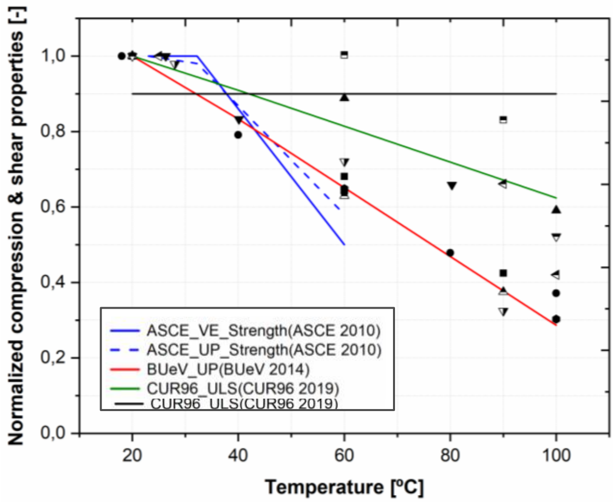
Longitudinal tensile strength



Longitudinal tensile modulus



Compressive/shear strengths



Reduction of matrix-dominated properties much higher than fibre-dominated

High scatter in reduction with temperature of both fibre- and matrix-dominated properties (likely due to differences in T_g of materials tested)

ASCE (2010), BUeV (2014), CUR96 (2019): in general, not accurate, often over-conservative, but sometimes non-conservative

4. Basis of Design – Definition of Conversion Factor η_{ct}

Fibre-dominated properties

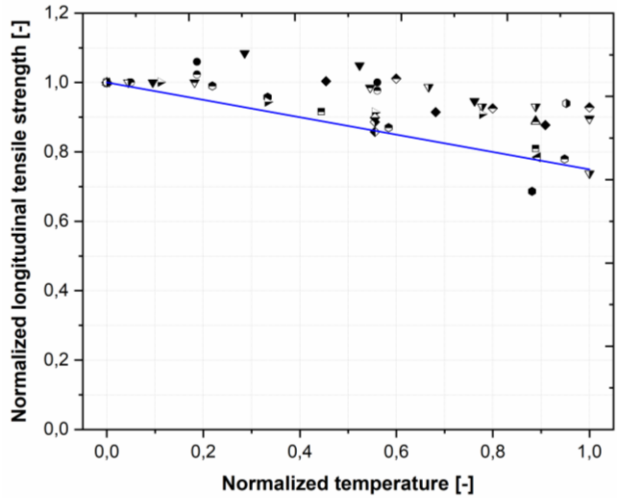
$$\eta_{\mathrm{ct}} = \min\left\{1{,}0 - 0{,}25 \cdot \boxed{\frac{T_{\mathrm{s}} - 20}{T_{\mathrm{g}} - 20}};\ 1{,}0\right\}$$

Normalized temperature

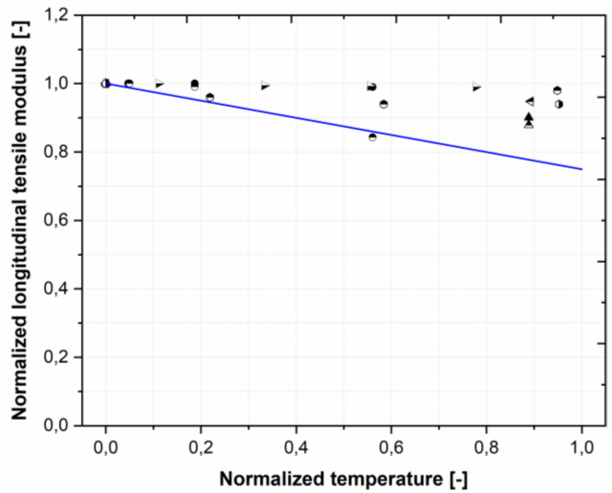
Matrix-dominated properties

$$\eta_{\mathrm{ct}} = \min\left\{1{,}0 - 0{,}80 \cdot \frac{T_{\mathrm{s}} - 20}{T_{\mathrm{g}} - 20};\ 1{,}0\right\}$$

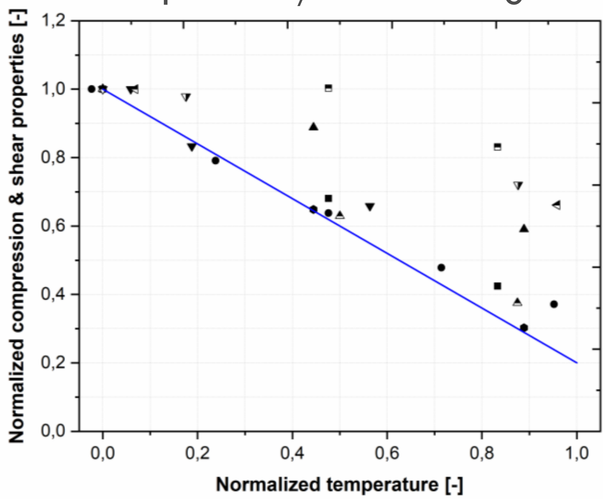
Tensile strength L



Tensile modulus L



Compressive/shear strengths



Suitability of proposed design-oriented temperature conversion factor (T_s, T_g)

Predictions obtained for both fibre- and matrix-dominated properties are (i) relatively precise and, at the same time, (ii) reasonably conservative

4. Basis of Design – Definition of Conversion Factor η_{cm}

Moisture

Three moisture exposure classes are defined according to the intensity and frequency of moisture exposure

Exposure classes	Influence of moisture
I	Indoor exposure
II	Outdoors exposure without (i) continuous exposure to water, (ii) permanent immersion in water, (iii) permanent exposure to a relative humidity higher than 80%, (iv) combined UV radiation and frequent freeze-thaw cycles
III	Continuous exposure to water (or seawater), or permanent immersion in water (or seawater), or permanent exposure to a relative humidity higher than 80% (material temperature up to 25 °C)

4. Basis of Design – Definition of Conversion Factor η_{cm}

Class II - outdoor exposure

Experimental durability studies (10) on GFRP materials under natural weathering (moisture, temperature variations, UV radiation), properties from standard tests:

- Fibre reinforcements: glass
- Resins: unsaturated polyester (UP), vinylester (VE)
- Manufacturing processes: pultrusion, vacuum infusion, hand layup
- Fibre volume content: 33% to 60%
- Exposure environments: Alpine (Switzerland) , Humid continental (Maine, USA), Mediterranean (Lisbon), Semi-continental (Milan), Temperature oceanic (Rotterdam), Temperate (Kyoto), Indoor (relatively high RH, 23°C)
- Exposure durations: up to 20 years
- Properties: tensile, flexural, shear, interlaminar shear
- Total number of data points: 211 (each is an average value, ~800 tests)

4. Basis of Design – Definition of Conversion Factor η_{cm}

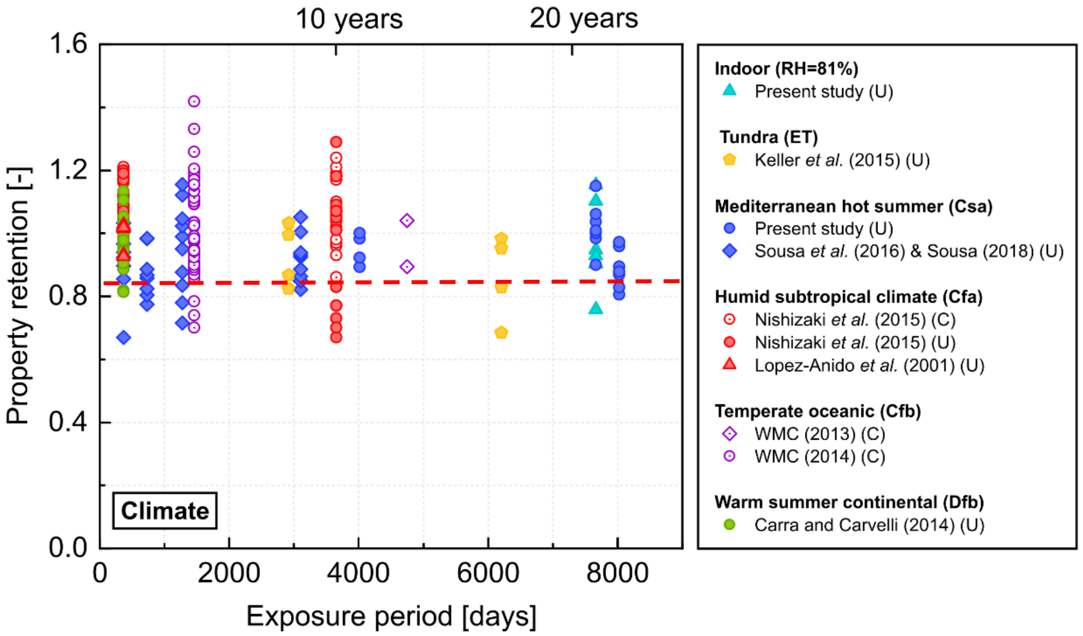
Class II - outdoor exposure

Lisbon shopping centre roof
(Mediterranean climate)

The Pontresina Bridge
(Switzerland, Alpine climate)

4. Basis of Design – Definition of Conversion Factor η_{cm}

Class II - outdoor exposure



Stiffness/strength retention (UP and VE resins) *vs.* exposure period for natural (outdoor) weathering, sorted by type of climate

Proposal for 50-year conversion factor

$\eta_{cm} = 0.85$

Lowest (individual) property retention ~60-65% (but retention up to ~140%)

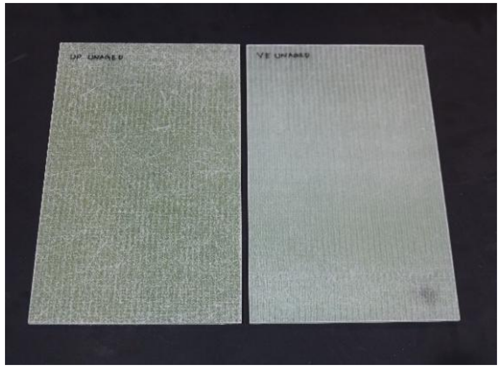
No clear property reduction trend with time of exposure

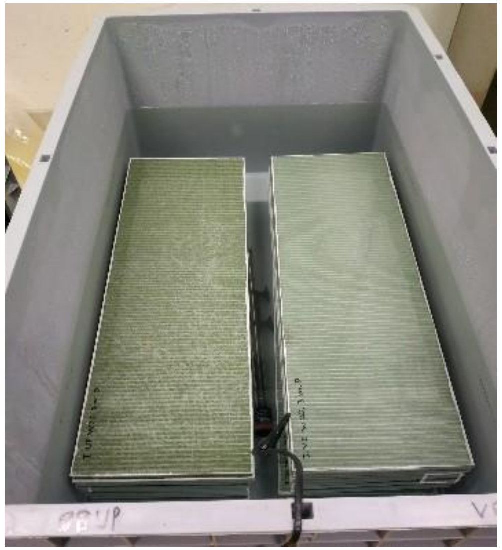
No clear influence of type of resin (UP *vs.* VE)

4. Basis of Design – Definition of Conversion Factor η_{cm}

Class III – immersion in water

Parameter	Experimental data
No. of studies	17
Resins	unsaturated polyester, vinylester
Fibre reinforcement	glass-fibre (E-glass)
Manufacturing processes	pultrusion, vacuum infusion, hand layup
Fibre content (V_f)	32 to 60%
Exposure duration	up to ~5000 days (~14 years)
Environments	water, seawater and saline solution at temperatures between 20-25 °C
Properties	tensile, flexural and in-plane shear strength and moduli; interlaminar shear strength
Total data points	515

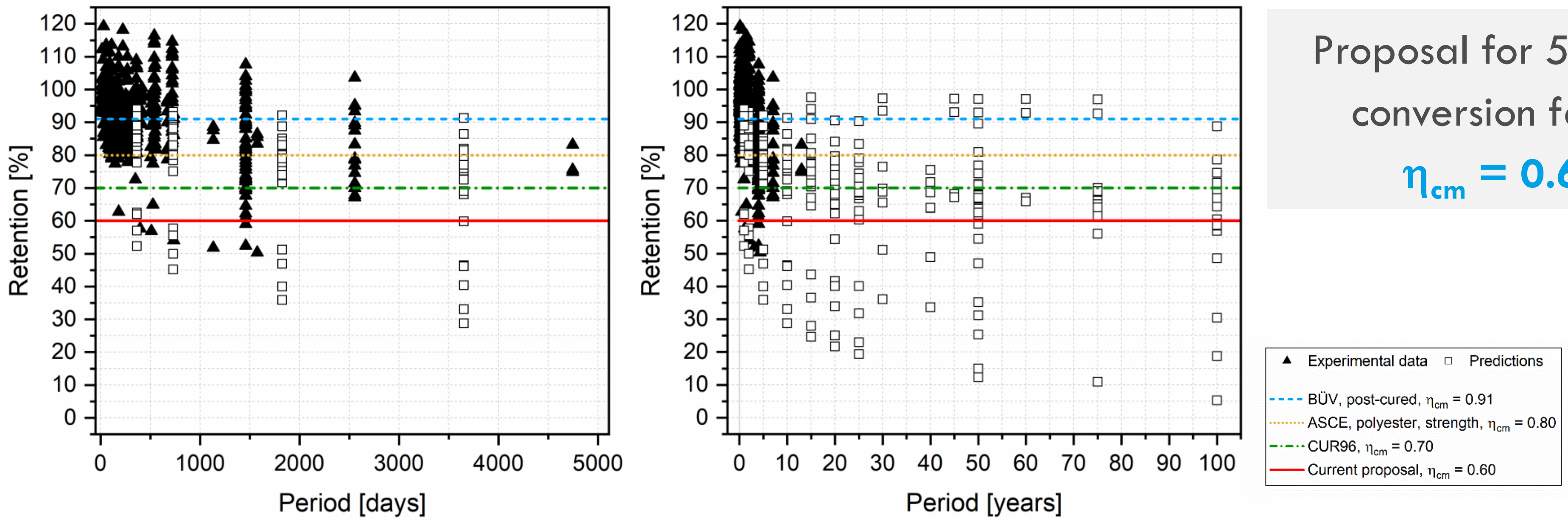




Water immersion of GFRP laminates made of polyester and vinylester resins

4. Basis of Design – Definition of Conversion Factor η_{cm}

Class III – immersion in water



Proposal for 50-year conversion factor

η_{cm} = 0.60

Very high scatter

Some reductions quite significant (generally, very thin laminates)

Conversion factors suggested in existing design guidelines may be nonconservative

[1] Different values may be used (i) based on tests (well-stablished protocols/methods) or (ii) with protective systems (effectiveness over design service life has to be guaranteed)

4. Basis of Design – Creep Effects

Considered in design for: (i) strength (creep rupture, ULS), limiting stress levels; and (ii) deformations (SLS), through a creep coefficient, $\phi(t)$ (large survey of test data)

$$X_{\mathrm{m}}(t)=\frac{X_{\mathrm{m}}(0)}{1+\phi(t)}$$

Table 4.7 — Values for the creep coefficient $\phi(t)$, for $t = 50$ years, for different elastic and shear moduli of pultruded composite profiles (glass, carbon or basalt fibres; fibre volume fraction of at least 35%; material temperature up to 25 °C; relative humidity up to 65%) *

Material	Property	$\phi(t = 50 \text{ years})$
Pultruded composite profiles	$E_{\mathrm{x}}^{\mathrm{full}}$	0,70
	$G_{\mathrm{xy}}^{\mathrm{full}}$	2,09
	$E_{\mathrm{x,t}}$	0,26
	$E_{\mathrm{x,c}}$	0,41

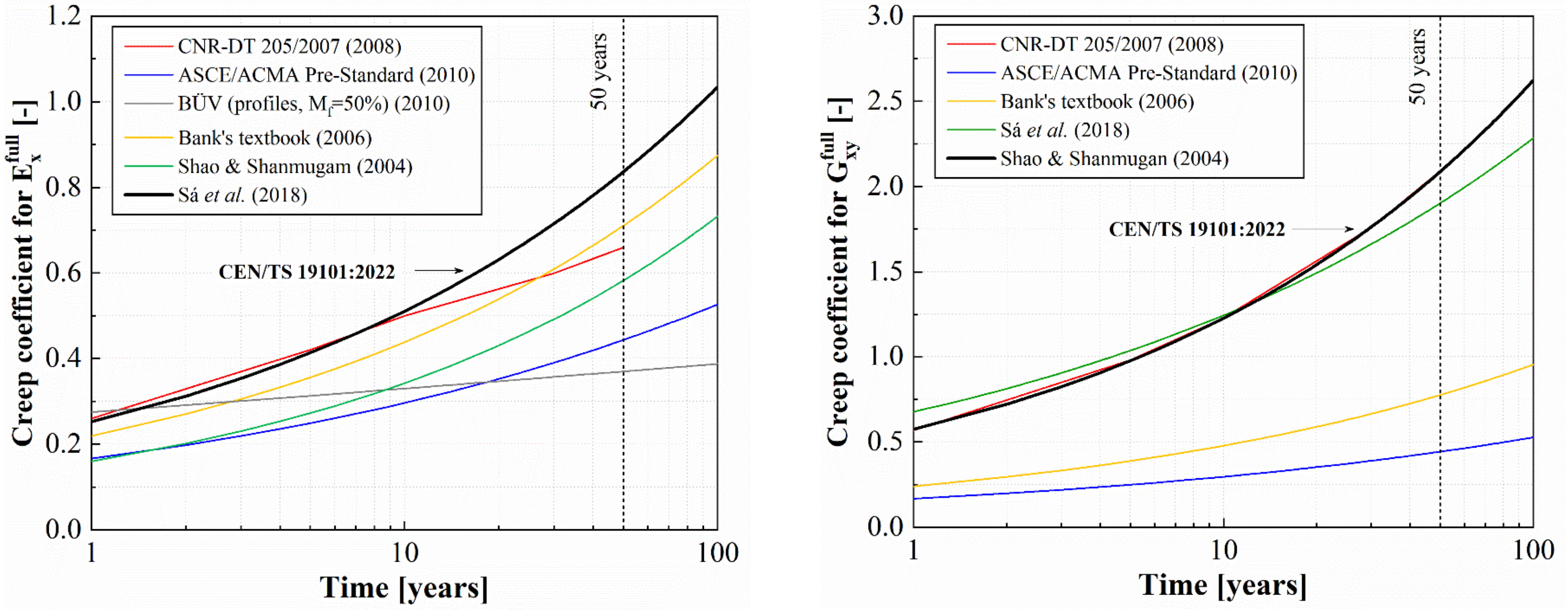
Further values also provided for composite laminates/plies and core materials

Values for additional periods in Annex A

4. Basis of Design – Creep Effects

Considered in design for: (i) strength (creep rupture, ULS), limiting stress levels; and (ii) deformations (SLS), through a creep coefficient, $\phi(t)$ (large survey of test data)

$$X_{\mathrm{m}}(t)=\frac{X_{\mathrm{m}}(0)}{1+\phi(t)}$$



Creep coefficients for pultruded GFRP profiles for E_x^{full} (left) and G_{xy}^{full} (right)

5. Materials

Composite, core and adhesive material properties should be determined from testing according to standard methods

$T_g > 60$ °C (DMA)

Table 5.1 — Laminate material properties *

Property	Symbol	Standard test method
In-plane tensile modulus (in x and y direction)	$E_{x,t}$, $E_{y,t}$	EN ISO 527
In-plane tensile strength (in x and y direction)	$f_{x,t}$, $f_{y,t}$	EN ISO 527
Out-of-plane tensile strength (in z direction)	$f_{z,t}$	ASTM D7291/D7291M
In-plane compressive modulus (in x and y direction)	$E_{x,c}$, $E_{y,c}$	EN ISO 14126
In-plane compressive strength (in x and y direction)	$f_{x,c}$, $f_{y,c}$	EN ISO 14126
In-plane shear modulus (xy plane)	G_{xy}	ASTM D7078/D7078M ASTM D5379/D5379M
In-plane shear strength (xy plane)	$f_{xy,v}$	ASTM D7078/D7078M ASTM D5379/D5379M
In-plane major and minor Poisson's ratio (xy plane)	ν_{xy}, ν_{yx}	EN ISO 527
Flexural strength (in x and y direction)	$f_{x,f}$, $f_{y,f}$	EN ISO 14125
Interlaminar shear strength (yz and xz planes)	$f_{yz,ILS}$, $f_{xz,ILS}$	EN ISO 14130
Density	ρ	EN ISO 1183-1
Glass transition temperature [a]	T_g	ISO 6721-11
Coefficient of linear thermal expansion (in x and y direction)	α_x, α_y	ISO 11359-2
Thermal conductivity [b]	λ	EN ISO 22007-2 EN ISO 22007-4

Annex B provides indicative properties for preliminary design

6. Durability

Potential effects, design options/recommendations and mitigation measures for different environmental conditions, acting in isolation or in combination:

- Temperature
- Moisture (humidity, water)
- Chemicals
- Ultraviolet (UV) radiation

Water immersion

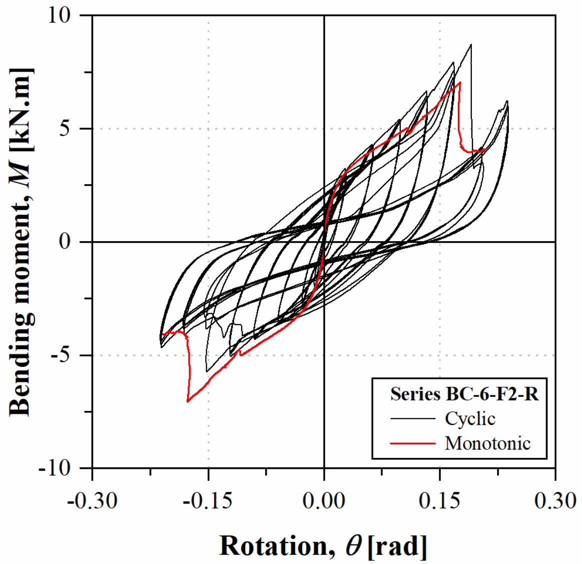
Acid exposure
(water treatment plant)

QUV exposure
(fibre blooming)

7. Structural Analysis

Examples of points highlighted:

- Orthotropic material properties
- Typical linear elastic behaviour
- Relevance of shear deformation
- Influence of temperature and moisture on material properties
- Viscoelasticity
- Possible non-linear behaviour of joints
- Composite action in hybrid-composite structures
- Second-order effects
- Imperfections



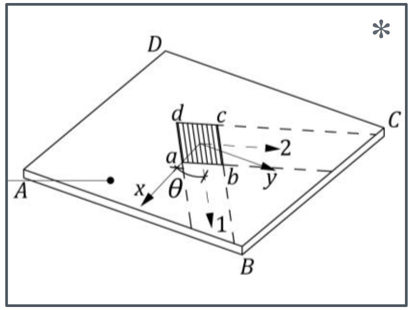
M-θ curves for beam-to-column joints with metallic cleats

8. Ultimate Limit States

Verifications for typical failure modes:

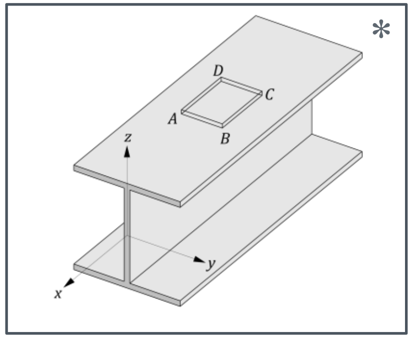
- **Laminates** (balanced symmetrical)

  in-plane (axial, shear, bending), out-of-plane (tensile, bending), interlaminar shear and combined stresses



- **Profiles**

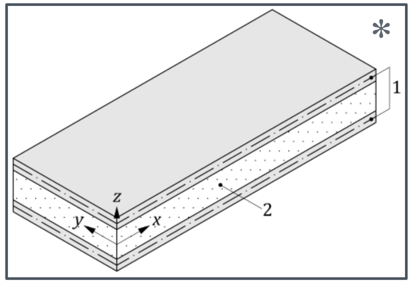
  axial force, bending, shear, transverse compression, torsion, combination of axial force and bending, and bending and shear



- **Sandwich panels**

  20 failure modes of components (face sheet, core, web), interface and entire panel (e.g. laminate wrinkling, core indentation, core punching)

  failure at face sheet-core interface shall not occur



8. Ultimate Limit States

Creep rupture – limits to sustained stresses (quasi-permanent combinations)

Design value of tensile[1] stress limit for creep rupture:

$$\sigma_{\mathrm{t,creep,Rd}} = k_{\mathrm{t,creep}} \frac{X_{\mathrm{t,k}} \cdot \eta_{\mathrm{c}}}{\gamma_{\mathrm{M,creep}}}$$

$$\gamma_{\mathrm{M,creep}} = 1{,}5$$

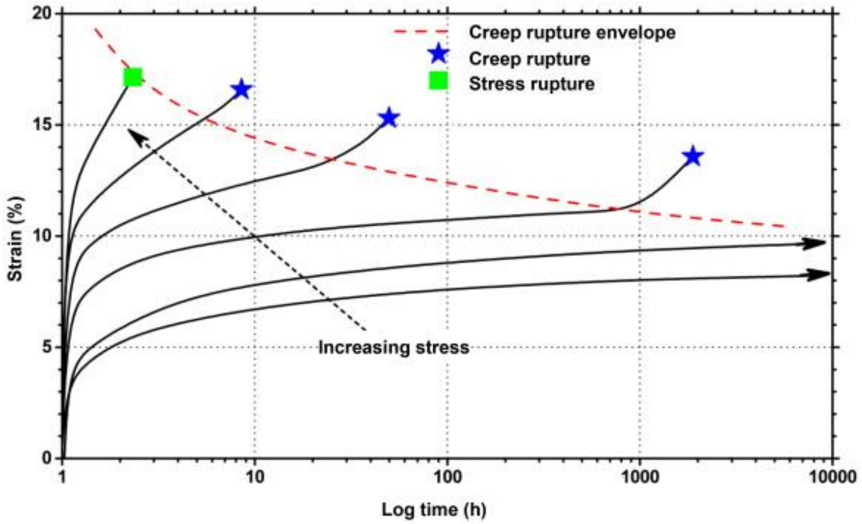


Table 8.3 — Strength reduction factor for tensile creep rupture for continuous unidirectional reinforcement, $k_{\mathrm{t,creep}}$, for different types of fibres, for a period of 50 years *

Type of fibre	Glass	Aramid	Basalt	Carbon
$k_{\mathrm{t,creep}}$	0,4	0,5	0,6	0,9

[1] For compression, $k_{\mathrm{c,creep}} = 0{,}75\ k_{\mathrm{t,creep}}$

9. Serviceability Limit States

Verifications for:

- **Deflections**

  relevance of creep, shear deformations
  (most often govern design of composite structures)

- **Vibrations**

  relevance for footbridges
  (damping ratios suggested)

- **Matrix cracking**

  possible relevance for in-service performance under exposure classes II and III
  (structures exposed to moisture)

10. Fatigue

Fatigue verification (including testing), conducted at structural member / joint level

Fatigue verification criterion: $$E_{\mathrm{d}}\left(\gamma_{\mathrm{Ff}} \cdot Q_{\mathrm{fat}}\right) / R_{\mathrm{d}} > 1{,}6 - 0{,}18 \cdot \lg N$$

Fatigue action model for traffic loads should be derived from the project specification and EN 1991-2 and take into account the mean stress level

Fatigue verification: $$E_{\mathrm{d}}\left(\gamma_{\mathrm{Ff}} \cdot Q_{\mathrm{fat}}\right) \leq \eta_{\mathrm{ct}} \cdot \eta_{\mathrm{cm}} \cdot R_{\mathrm{f,k}} / \gamma_{\mathrm{Mf}}$$

$R_{\mathrm{f,\,k}}$ characteristic value of fatigue resistance of the member or joint, obtained from member or joint testing, at constant amplitude (the Palmgren-Miner linear damage hypothesis is not considered applicable for composites)

10. Fatigue

Table 10.1 — Partial factors for fatigue resistance, γ_{Mf} *

Inspection and access	Fail-safe	Non-fail-safe
Member or joint subjected to periodic inspection and maintenance [a]; detail accessible.	1,5	2,0
Member or joint subjected to periodic inspection and maintenance [a]; limited accessibility.	2,0	2,5
Member or joint not subjected to periodic inspection and maintenance.	2,5	3,0
[a] According to maintenance plan		

Qualification and proof testing is distinguished

Qualification testing (bridges): required number of fatigue tests and fatigue cycles specified according to traffic category, for 50- and 100-year design service life

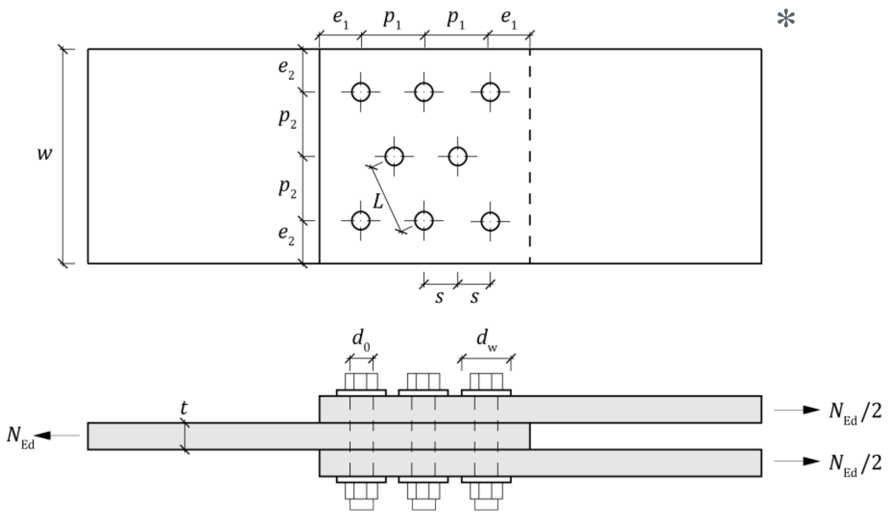
Proof testing: defined case by case in project-specific quality plan

11. DETAILING (+ ANNEX E)

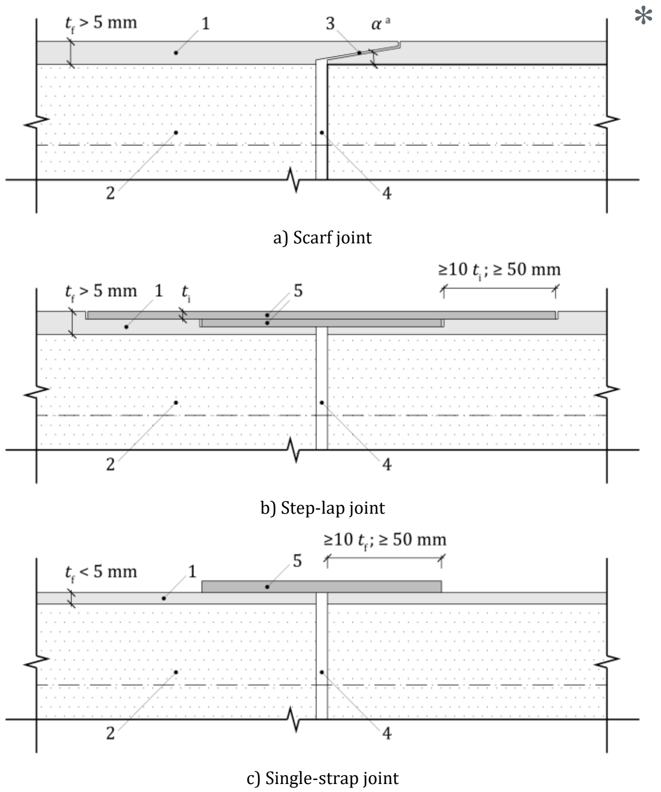
Provisions for laminates, profiles, sandwich panels, bolted joints, bonded joints

Aim: to minimize stress concentrations and effects of environmental conditions, and to address tolerances and imperfections

Generic details for bridges (Annex E)



Double-lap bolted joints: bolt diameters, hole clearances, distances between holes and from edges



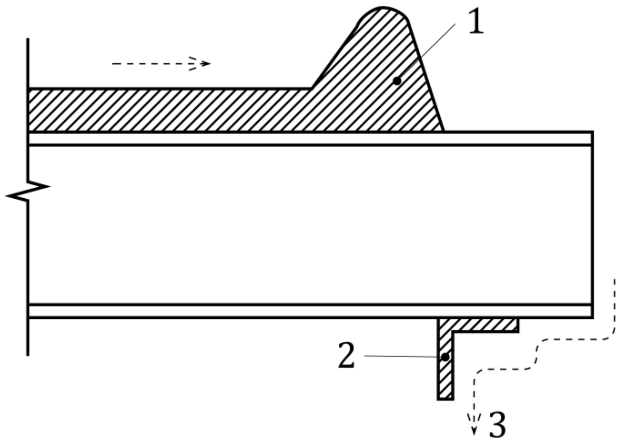
Sandwich panels: face-sheet connections

11. DETAILING (+ ANNEX E)

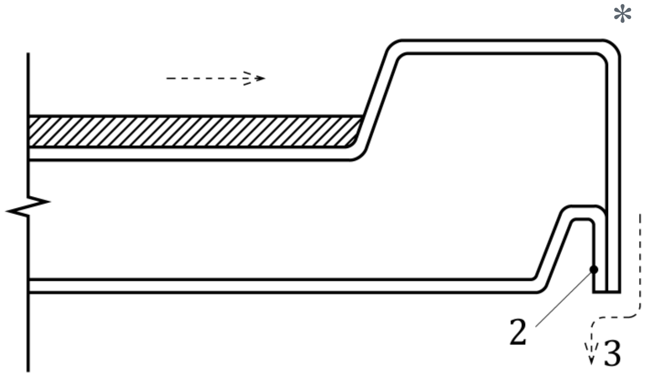
Provisions for laminates, profiles, sandwich panels, bolted joints, bonded joints

Aim: to minimize stress concentrations and effects of environmental conditions, and to address tolerances and imperfections

Generic details for bridges (Annex E)



(a) constant deck thickness



(b) variable deck thickness

Details for bridge parapets

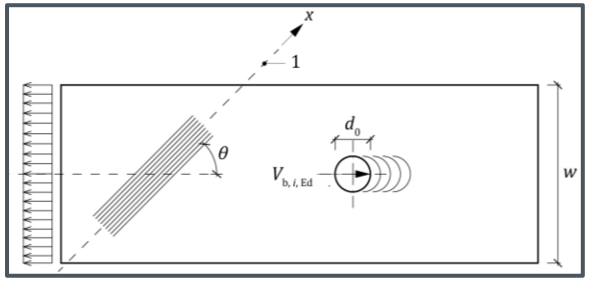
12. Connections and Joints

Bolted, adhesive and hybrid bolted-adhesive connections and joints

Bolted joints:

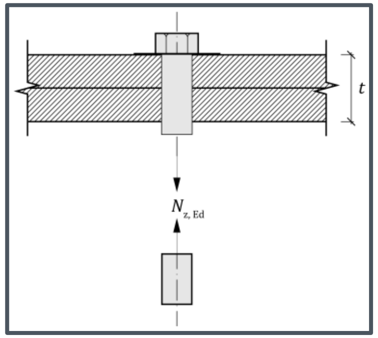
Connections under in-plane actions (laminates):
- Net-tension
- Pin-bearing
- Shear-out
- Block shear

*



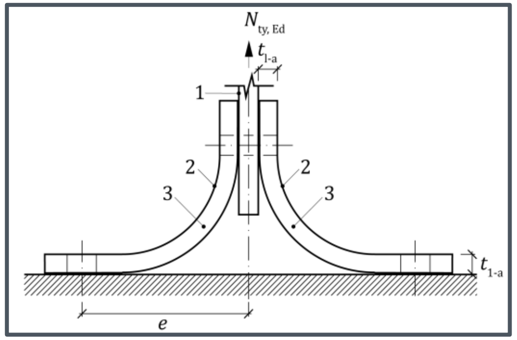
Connections under out-of-plane actions:
- Pull-out failure (laminate)
- Bolt failure in tension

*



Web cleat joints:
- Shear failure
- Tying force failure

*



12. Connections and Joints

Bolted, adhesive and hybrid bolted-adhesive connections and joints

Adhesive joints:

- Fail-safe condition: composite structures comprising adhesive joints shall be designed as fail-safe (joint failure shall not result in failure of the structure or critical parts thereof)
- Accidental situation: failure of adhesive joint is considered an accidental situation according to EN 1990
- Interface failure not allowed: failure mode shall be either cohesive in adhesive or fibre-tear in adherend (appropriate material selection and surface preparation required)

12. Connections and Joints

Design value of adhesive connection resistance

$$R_{\mathrm{ac,Rd}} = \frac{\eta_{\mathrm{c}}}{\gamma_{\mathrm{M,ac}}} \cdot R_{\mathrm{ac,k}}$$

Table 12.4 — Partial factors for adhesive connection resistance, $\gamma_{\mathrm{M,ac}}$ *

Inspection and access	Fully controlled application	Partially controlled application
Connection subjected to periodic inspection and maintenance [a]; adhesive connection accessible.	1,5	2,0
Connection subjected to periodic inspection and maintenance [a]; limited accessibility.	1,7	2,2
Connection not subjected to periodic inspection and maintenance.	2,0	2,5
[a] According to maintenance plan		

Partial factor $\gamma_{M,ac}$ depends on:

- Type of inspection and maintenance & accessibility of adhesive connection
- Application conditions (reproducible process parameters)

12. Connections and Joints

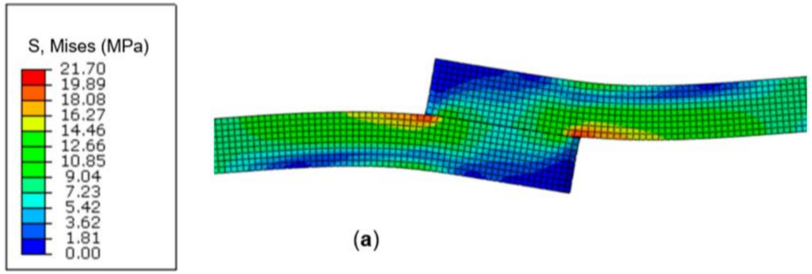
Methods for design of adhesive joints:

1. Design assisted by testing
2. Design based on stress analysis
3. Design based on fracture mechanics

Experimental validation required

Stress-based failure criterion:

$$\left(\frac{\sigma_{z,t,Ed}}{f_{z,t,d}}\right)^2 + \left(\frac{\tau_{xy,Ed}}{f_{xy,v,d}}\right)^2 \leq 1.0$$

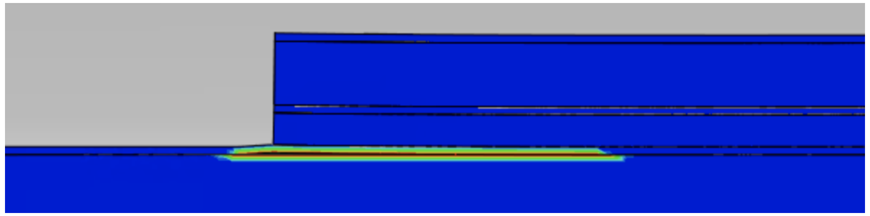


(Guilpin et al. 2019, Polymers, DOI: 10.3390/polym11091531)

Fracture-mechanics-based failure criterion:

$$\left(\frac{G_{I,Ed}}{G_{Ic,Rd}}\right)^m + \left(\frac{G_{II,Ed}}{G_{IIc,Rd}}\right)^n \leq 1{,}0$$

(requires VCCT and/or CZM)



(Pavlovic, Christoforidou, Keller, ECCM20, 2022)

Annex D. Structural Fire Design

Overall approach and structure consistent with fire parts of other Eurocodes

Scope: structures fulfilling load-bearing function, separating function or both

Fire exposure: accidental design situation

Fire design: “Advanced design methods” and/or “Testing”

(“Tabulated design data” and “Simplified design methods” not yet available)

Material properties:

- Thermal (emissivity, thermal conductivity, specific heat, density)
- Mechanical (strength and stiffness, thermal expansion coefficient)

  (Indicative temperature-dependent values provided for selected materials)

III. BACKGROUND DOCUMENT

Background Document

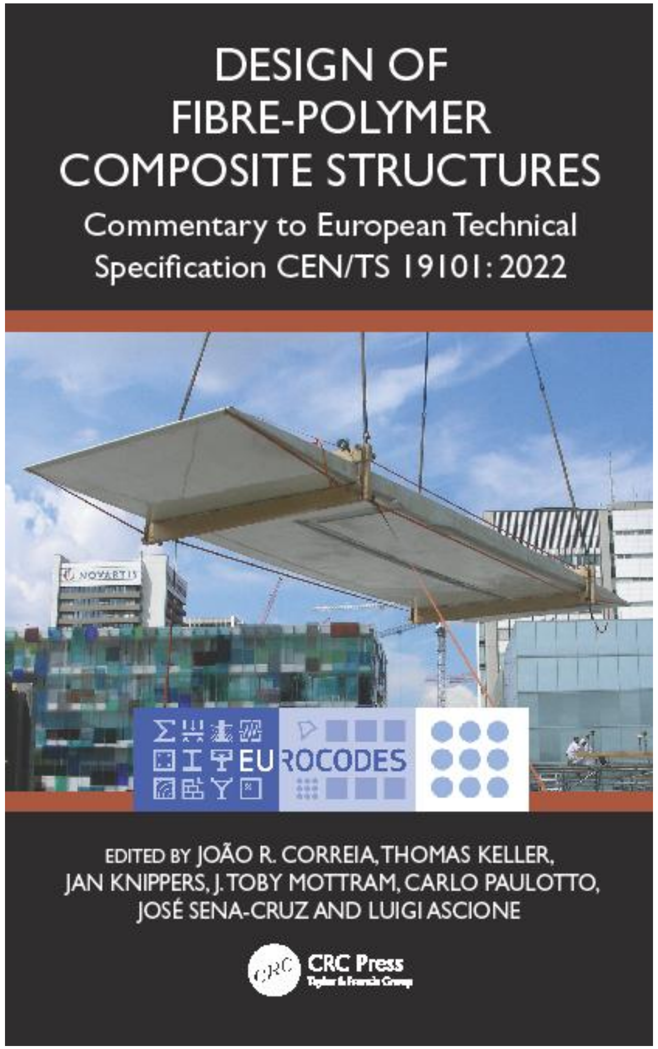
Content with ~1000 pages

~400 Background Reports (BRs) for all relevant paragraphs of TS

BRs prepared by PT members with support of WG4 members and external experts

Each BR reviewed by at least 2 reviewers (PT, WG4, external experts)

Available as book, in open-access format
(CRC Press, end 2024)



5. MATERIALS

Heading information

TS Content

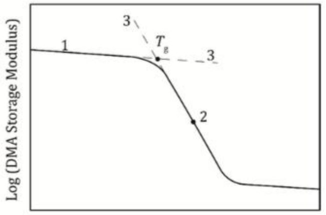
Commentary

Background Report
TS "Design of Fibre-Polymer Composite Structures"

REPORT NUMBER	BR_5.1_PAR_1
CLAUSE / ANNEX	5. MATERIALS
SUB-CLAUSE	5.1 Glass transition temperature
PARAGRAPH	(1)
AUTHOR(S)	Thomas Keller, Carlo Paulotto, Enrique Navarro
REVIEWER(S)	João Ramôa Correia, José Sena-Cruz
DATE	31 March 2021

CONTENT

(1) The glass transition temperature (T_g) of composite, polymeric core and adhesive materials shall be the temperature at the onset of the storage modulus decay of the unaged material, determined based on ISO 6721-11 and as illustrated in Figure 5.1. It shall be at least 20 °C above the maximum material temperature in service conditions (T_s, see 1.1(4)), and it should be at least 60 °C.



Key
1 Glassy state
2 Inflection point in glass transition region
3 Tangent lines

Figure 5.1 — Determination of glass transition temperature (T_g)

NOTE: The glass transition temperature is determined as the temperature at the intersection of two tangent lines of the storage modulus curve, in a plot of the logarithm of the storage modulus vs. the linear temperature, obtained from Dynamic Mechanical Analysis (DMA). The first tangent line approaches the curve in the glassy state, while the second tangent line is constructed at the inflection point in the glass transition region. Further guidance can be found in ASTM D7028, Appendix.

Determination of the glass transition temperature (T_g)

Background

The DMA method instead of the DSC method is used to determine the glass transition temperature (T_g) of fibre-polymer composites, since the former method is based on a mechanical property, i.e. the storage modulus (or stiffness), and not on a physical property, i.e. the heat capacity, as in the latter case.

Most often the criterion for the selection of T_g from DMA data is either (i) the peak of the loss modulus curve, or (ii) the inflection point of the storage modulus curve, or (iii) the peak of the loss factor (tan δ) curve, as defined in Fig. 1 of ISO 6721-11 [1], i.e. temperatures (1)-(3) are considered as T_g.

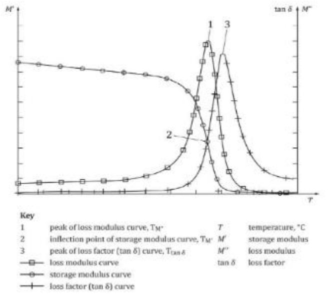


Fig.1 in ISO 6721-11:2019

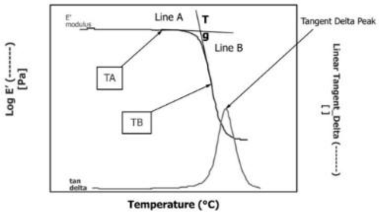


Fig.1 in ASTM D7028-07(2015)

As can be seen in Fig. 1 of ISO 6721-11, the storage modulus, i.e. stiffness, may already have decreased at these temperatures, i.e. (1)-(3), to values below around 50% of the stiffness in the glassy state, i.e. at ambient temperature. Taking one of these temperatures as T_g is thus not appropriate as a basis of SLS and ULS verifications.

The T_g-value is therefore defined as the lower value at the onset of the storage modulus decay, as shown in Fig. 5.1 and explained in the NOTE of the TS, and as also defined in Fig. 1 of ASTM D7028 [2]. Further guidance concerning the determination of the two tangent lines in cases not so obvious as shown in Fig. 5.1 is given in the Appendix of ASTM D7028. The possibility of taking a T_g-onset value is also mentioned in NOTE 4 to Section 4 of ISO 6721-11, it is however not clearly specified how this value can be obtained.

The use of the Heat Distortion Temperature (HDT) as an estimate of T_g is not permitted due to the following reasons:

1) HDT defines a temperature at which a given sample geometry exhibits a specific deformation under a fixed stress; the test essentially measures the temperature at which a material achieves a specific modulus. Many designers and engineers treat this property as an indicator of long-term elevated-temperature performance and specify materials accordingly. This however leads to product failures in some cases and costly over-engineering in other cases (see [3], p. 3);
2) No strong correlation exists between HDT and T_g (as defined above);
3) Aspects such as temperature conversion factors that are defined based on T_g (as defined above).

References

[1] ISO International Organization for Standardization. ISO 6721-11:2019. *Plastics – Determination of dynamic mechanical properties – Part 11: Glass transition temperature*. Geneva: ISO, 2019.

Background Report
TS "Design of Fibre-Polymer Composite Structures"

[2] ASTM American Society for Testing and Materials. D7028 - 07(2015). *Standard Test Method for Glass Transition Temperature (DMA T_g) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA)*. West Conshohocken: ASTM International, 2015. DOI: 10.1520/D7028-07E01R15.
[3] SEPE, M.P. The Usefulness of HDT and a Better Alternative to Describe the Temperature Dependence of Modules. *SAE Technical Paper Series*. 1999, **277**(1), 1-10. ISSN: 0148-7191

60 °C value

The T_g-value, as defined above, should be at least 60 °C. At this value, in the case of cold-curing, it is assumed that the resin is almost fully cured.

In [1], the 60°C-value has been confirmed for a cold-curing epoxy adhesive. A curing degree of almost 1.0 was obtained at T_g=60°C (Fig. 20 in [1]); this T_g-value has been obtained from DSC however. T_g-values obtained from DSC are normally higher than DMA T_g-values as defined above. In [1], the DSC values were 5-10°C higher than the DMA values (Fig. 11 in [1], C21 values). Full curing was thus achieved at a DMA T_g-value, as defined above, of around 50°C already.

References

[1] SAVVILOTIDOU, M., et al. Effects of aging in dry environment on physical and mechanical properties of a cold-curing structural epoxy adhesive for bridge construction. *Construction & Building Materials*. 2017, **140**, 552-561. Available from: https://doi.org/10.1016/j.conbuildmat.2017.02.063

20 °C value

The T_g-value, as defined above, should be at least 20 °C above the maximum service temperature since the storage modulus, and thus stiffness, may already have started decreasing if the T_g-value would be selected equal to the service temperature. Such a potential decrease may be particularly relevant in matrix-dominated properties.

A similar maximum service temperature of T_g-20°C is defined in [1]. T_g is obtained from the storage modulus curve of ISO 6721-11, it is however not specified which value is meant, the onset or the inflection point value. According to [2], the maximum service temperature should be 10-20°C below T_g, it is however not specified which T_g is meant.

References

[1] CROW-CUR Recommendation 96:2019. Fibre-reinforced polymers in buildings and civil engineering structures. Ede: CROW, 2019.
[2] CLARKE, John L. (ed.). *Structural design of polymer composites: EUROCOMP Design code and handbook*. London: E & FN Spon, 1996. ISBN 0 419 19450 9.

IV. WORKED EXAMPLES

WORKED EXAMPLES

15 Worked Examples for typical design cases

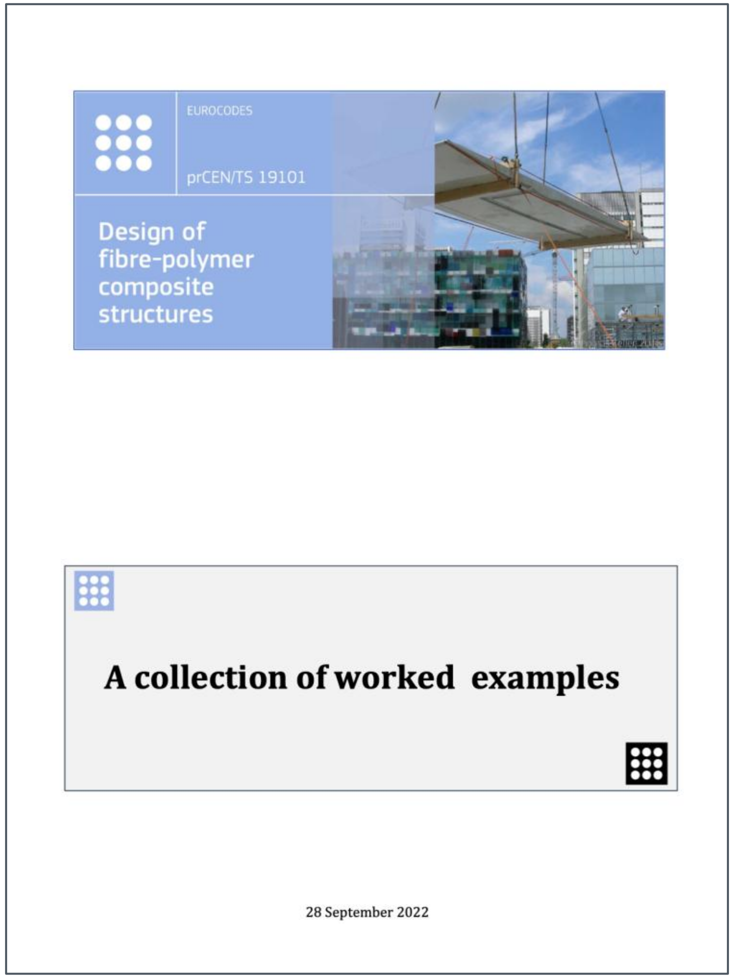
- Type A (11): step-by-step detailed examples at structural member or joint levels, illustrating specific provisions of TS (as in a textbook)
- Type B (4): more complex examples for design of full-scale structures or parts of structures

Content with ~400 pages

WEs prepared by PT/WG4 members and external experts

Each WE reviewed by at least 2 reviewers (PT, WG4, external experts)

Available as book, in open-access format (CRC Press, end 2024)



EXAMPLE NO. 03	
TITLE	ULS verifications of a simply supported fibre-polymer composite profile with double symmetric cross-section subjected to axial compression
AUTHOR(S)	Mário Sá, João Ramôa Correia
REVIEWER(S)	Luigi Ascione, José Gonilha
DATE	06 May 2021 (version 2.0)
TS DRAFT NO.	Final revised draft, 30/04/2021
UNITS	Length / Force / Stress: [mm] / [N] / [MPa]

1. Data of the problem

In this example, Ultimate Limit States (ULS) verifications are performed for a simply supported fibre-polymer composite profile (column), with double symmetric cross-section, subjected to concentric axial compression.

The column is assumed to support the beams of a floor (beams length of 4000 mm and 2400 mm) belonging to a two-storey residential building structure, with the modular floor plan illustrated in Figure 1. The profile column has length L of 2800 mm (in the longitudinal direction, x-axis), corresponding to the nominal storey height H.

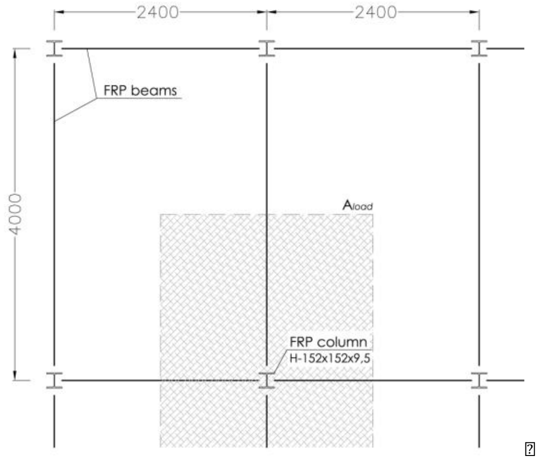


Figure 1: Floor scheme of the two-storey building (dimensions in mm).

The column consists of a fibre-polymer composite H-profile (wide-flange) with the following characteristics:

- Manufacturing process: pultrusion
- Matrix: isophthalic polyester resin
- Fibre reinforcement: E-glass rovings and woven cross-ply mats
- Fibre volume fraction (V_f): 50%
- Density (γ_{GFRP}): 18 kN/m³

and the cross-section (152×152×9,5 mm) has the following dimensions:

EXAMPLE NO. 03: *ULS verifications of a simply supported fibre-polymer composite profile with double symmetric cross-section subjected to axial compression*

Regarding the ULS verifications, the resulting axial load for the fundamental design situation is as follows:

$$F_d = \gamma_G \left(g_{sw,k} + g_{opl,k}\right) + \gamma_Q q_k = 1{,}35\cdot(0{,}42+19{,}2)+1{,}5\cdot 38{,}4 = 84{,}1\ \text{kN},$$

which corresponds to the design value of the compressive force at the bottom cross-section of the column: $N_{c,Ed} = 84{,}1$ kN.

In addition, the resulting axial load for the quasi-permanent combination of actions is as follows:

$$N_{c,qper} = \left(g_{sw,k} + g_{opl,k}\right) + \psi_{1,1}\cdot q_k = (0{,}42+19{,}2)+0{,}3\cdot 38{,}4 = 31{,}1\ \text{kN}$$

Other relevant data:

- Service temperature, $T_s = 20\ ^{\circ}\text{C}$;
- Glass transition temperature, $T_g > 100\ ^{\circ}\text{C}$;
- Exposure class: 1.

Subclause 4.4.2

2. Characteristic values of the material properties

This section shows the calculation procedure to obtain the characteristic values of the different material properties of the fibre-polymer composite profile's laminates. This calculation is exemplified for the characteristic value of the in-plane compressive strength in the x-direction of the fibre-polymer composite laminates $f_{x,c,k}$.

From the material testing, an average value of 441,5 MPa was obtained for the in-plane compressive strength in the x-direction of the laminates, $f_{x,c,m}$, with a coefficient of variation $V_{x,exp} = 6{,}5\%$. The characteristic value of the resistance (5% fractile) is given by:

Annex D of EN 1990

$$f_{x,c,k} = f_{x,c,m}\cdot\exp\left\{-k_n\cdot\sqrt{\ln\left(1+V_{x,exp}^2\right)} - \frac{\ln}{2}\left(1+V_{x,exp}^2\right)\right\}$$

Table D1 of EN 1990

Since the number of tested samples (n) is 10, $k_n = 1{,}92$. Thus, the characteristic value of the in-plane compressive strength in the x-direction $f_{x,c,k}$ is equal to:

$$f_{x,c,k} = f_{x,c,m}\cdot\exp\left\{-k_n\cdot\sqrt{\ln\left(1+V_{x,exp}^2\right)} - \frac{\ln}{2}\left(1+V_{x,exp}^2\right)\right\} =$$

$$f_{x,c,k} = 441{,}5\cdot\exp\left\{-1{,}92\cdot\sqrt{\ln\left(1+0{,}065^2\right)} - \frac{\ln}{2}\left(1+0{,}065^2\right)\right\} = 388{,}9\ \text{MPa}$$

Subclause 4.4.5

Paragr. 4.4.5(3)

3. Material partial factor

This section shows the procedure to obtain the material partial factor values for the different material properties of the fibre-polymer composite laminates. This is exemplified for the characteristic value of the in-plane compressive strength in the x-direction of the laminates $f_{x,c,k}$.

To account for the statistical uncertainty in the coefficient of variation, the value of $V_{x,exp}$ should be multiplied by the factor f_{V_x}.

3

EXAMPLE B1	
TITLE	Ultimate Limit State (ULS) verifications for bolted connections of pultruded profiles of a truss bridge with a span length of 13.50 m.
AUTHOR(S)	Matthias Oppe, Reza Haghani
REVIEWER(S)	Toby Mottram, Jan Knippers
DATE	30 January 2022
TS DRAFT NO.	FprCEN/TS 19101: 2021, 2021-11
UNITS	Length / Force / Stress: [mm], [m] / [kN] / [MPa]

1. Data of the problem

In this example, Ultimate Limit State (ULS) verifications are performed for bolted connections of pultruded profiles of a truss footbridge, shown in Figure 1 for an isometric view and in Figure 2 for an engineering drawing of the side view). The bridge has a span length of 13,50 m. The depth of the bridge from surface of deck to top of handrails is 1,1 m.

The trusses are composed of upper (special handrail profile) and lower chords, which are connected by means of diagonal and vertical hollow box profile elements. The lower chord consists of two U-profiles back-to-back and separated by the vertical elements, as seen in Figure 3 for a plan view of the footbridge cross-section.

The fibre-polymer composite elements are

- Fibre reinforcement: E-glass fibre rovings and mats;
- Matrix: polyester resin (UP);
- Manufacturing process: pultrusion process;
- Fibre volume fraction: 65%.

Note that the mechanical properties used in the design calculation are for illustration purposes only and are not necessarily actual characteristic properties of pultruded profiles.

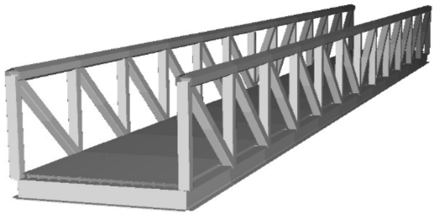


Figure 1 – Isometric view of truss footbridge

EXAMPLE B2	
TITLE	ULS verifications of a GFRP footbridge
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DATE	December 2021
TS DRAFT NO.	FprCEN/TS 19101: 2021, 2021-11
UNITS	Length / Force / Stress / Mass per Unit Area : [mm] / [N] / [MPa] / [g/m^2]

1. Data of the problem

In this example, Ultimate Limit State (ULS) verifications are performed for a pedestrian GFRP bridge. In our case study, we are interested in the verification of only one span of the bridge (isostatic span) which presents the following characteristics:

- Total length *L* (x) = 21 100 [mm];
- Width *w* (x) = 2400 [mm];
- Fibre reinforcement: E-glass fibres;
- Matrix: polyester resin;
- Manufacturing process: vacuum infusion.

The bridge is a sandwich structure. The cross-section of the bridge is given in figure 1. Four parts can be identified:

- Top and bottom skins (in blue colour);
- External webs (in green colour);
- Flange (in red colour);
- Internal webs (in grey colour).

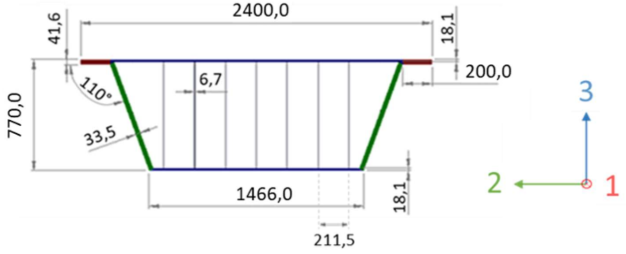


Figure 1 – Cross-section of the footbridge.

The top and bottom skins are structurally most effective (i.e. fibres are concentrated in these skins). For an effective transfer of the shear forces, the FRP webs are connected to the top and the bottom skins. A foam core material is present between each web but it is supposed to be non-structural (only acts as a placeholder during construction).

Each bridge part (namely each skin, flange and web) consists of a combination of a number of UD plies in different directions. The combination and the total thickness of each part are summarized in table 1.

V. CONCLUDING REMARKS AND FUTURE WORK

V.1 Concluding Remarks

The European Technical Specification CEN/TS 19101:2022 is a major step forward for the adoption of fibre-polymer composite structures in civil engineering

Compared to the first step ('Prospect'), there are many improvements:

(i) Basis of design (partial factors, conversion factors, creep coefficients); (ii) ULS of sandwich structures;
(iii) Creep rupture; (iv) Fatigue; (v) Adhesive joints/ connections; (vi) Detailing; (vii) Structural fire design.

The TS is complemented by a Background Document, providing additional information for the main paragraphs, justifying the decisions made, the values selected, and highlighting research needs

To support designers, Worked Examples were prepared to illustrate the application of the TS clauses

V.1 Concluding Remarks

The following factors explain the success of this project:

- Commitment and "balanced" composition of PT/WG4 (academia, designers, manufacturers, contractors)
- Close collaboration between different stakeholders
- No "restrictions" associated to pre-existing standards
- Specialized support of other SCs and WGs of CEN for critical aspects (basis of design, fatigue, fire)

The following difficulties were encountered:

- Lack of comprehensive/validated data at material and structural scales (resistance models, durability, fatigue)
- Lack of technical knowledge (seismic design, fire design)

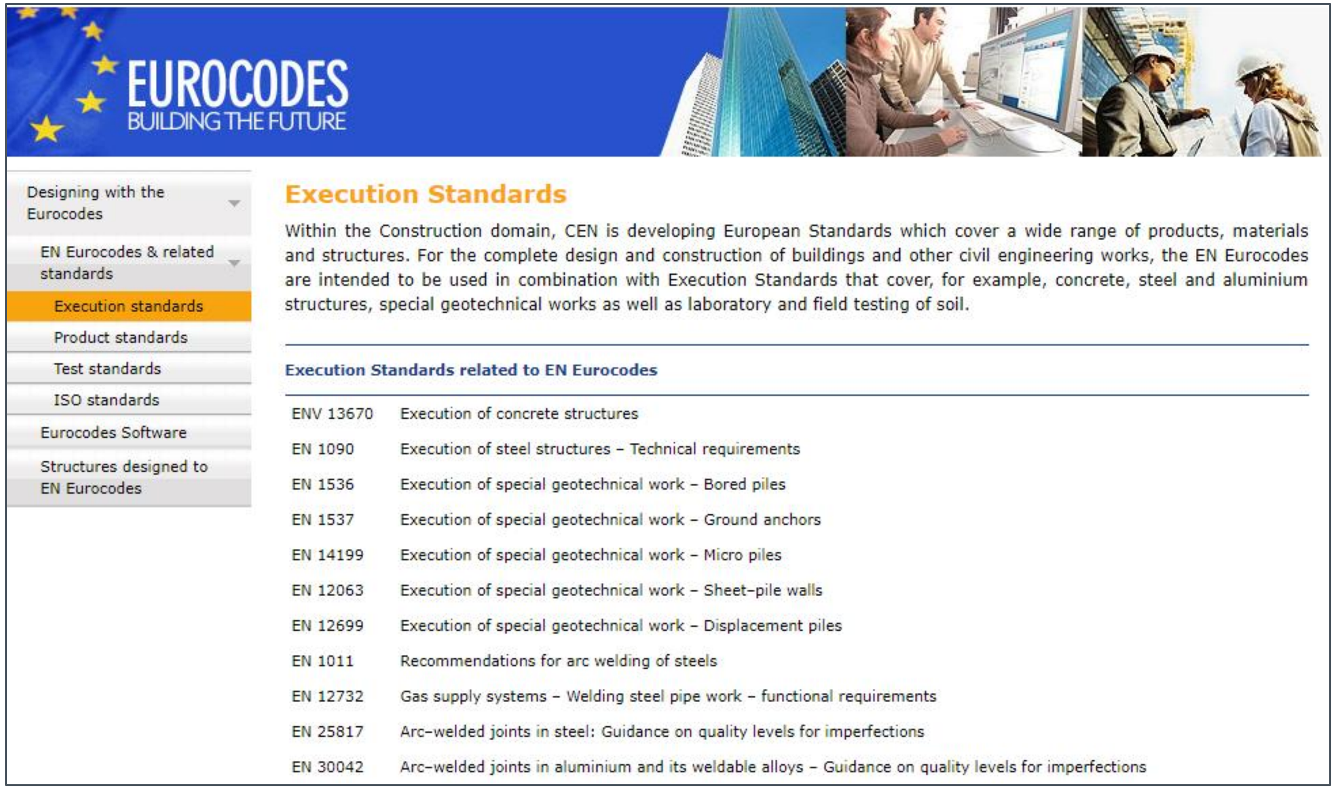
V.2 Future Work (2025-26)

Conversion of TS into Eurocode:

- Re-calibration of γ_{Rd} for some resistance models
- Re-definition of η_{c} for temperature and moisture (differentiating between fibre- and matrix-dominated properties) – economy, sustainability
- Additional provisions for profiles:
  - resistance to web crippling
  - more combined internal forces
  - more cross-sections

V.2 Future Work (2025-26)

Execution provisions will also be prepared and included in a new part, with input from all stakeholders, including contractors and designers.



Execution Standards

Within the Construction domain, CEN is developing European Standards which cover a wide range of products, materials and structures. For the complete design and construction of buildings and other civil engineering works, the EN Eurocodes are intended to be used in combination with Execution Standards that cover, for example, concrete, steel and aluminium structures, special geotechnical works as well as laboratory and field testing of soil.

Execution Standards related to EN Eurocodes

ENV 13670	Execution of concrete structures
EN 1090	Execution of steel structures – Technical requirements
EN 1536	Execution of special geotechnical work – Bored piles
EN 1537	Execution of special geotechnical work – Ground anchors
EN 14199	Execution of special geotechnical work – Micro piles
EN 12063	Execution of special geotechnical work – Sheet-pile walls
EN 12699	Execution of special geotechnical work – Displacement piles
EN 1011	Recommendations for arc welding of steels
EN 12732	Gas supply systems – Welding steel pipe work – functional requirements
EN 25817	Arc-welded joints in steel: Guidance on quality levels for imperfections
EN 30042	Arc-welded joints in aluminium and its weldable alloys – Guidance on quality levels for imperfections

Thank you!

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