Advanced Composites in Engineering Structures

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Lecture VII: Durability and long-term behavior of composites

EPFL

CCLAB Composite Construction Laboratory

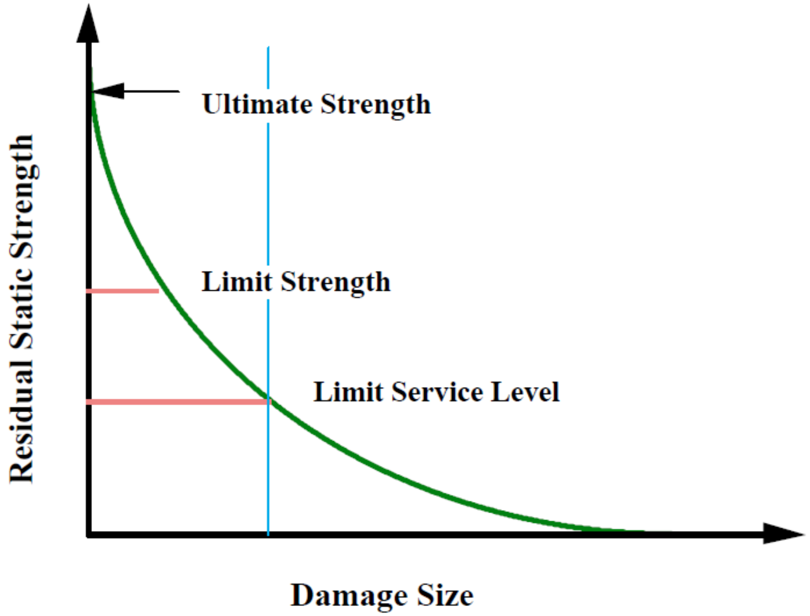
Outline

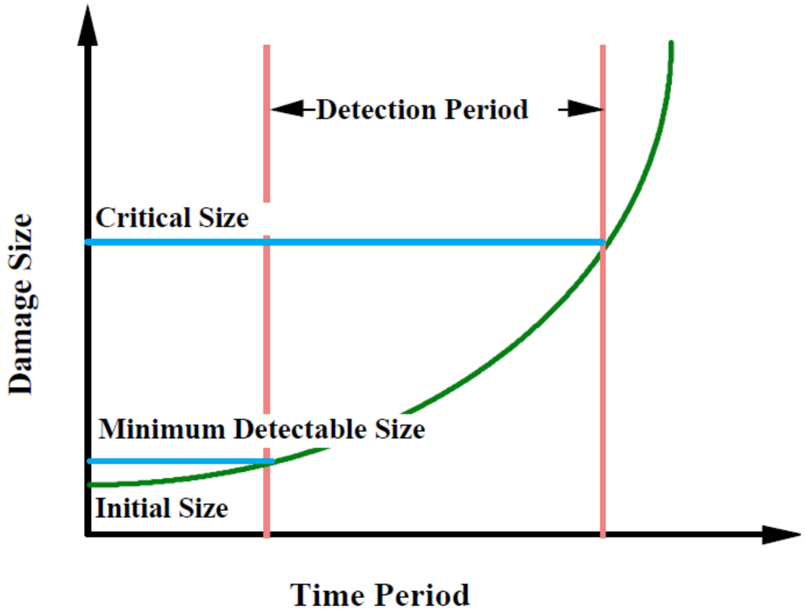
- **Durability**
  - Introductory aspects
  - Environmental degradation factors
    - Thermal effects
    - Moisture
    - Chemicals
    - UV exposure
  - How durability is addressed by the Codes

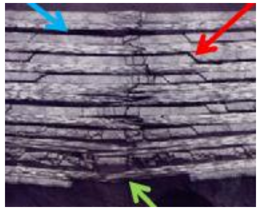
- **Creep**
  - Phenomenon
  - How creep is addressed by the Codes

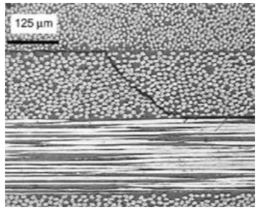
What is Durability?

"***Durability*** *of a* *<u>material, component or structure</u>* *is defined as its* ***ABILITY TO RESIST*** *cracking, oxidation, chemical degradation, delamination, wear, and/or the effects of foreign object damage for a* ***SPECIFIED PERIOD OF TIME****, under the appropriate* ***LOAD CONDITIONS****, under specified* ***ENVIRONMENTAL CONDITIONS***."









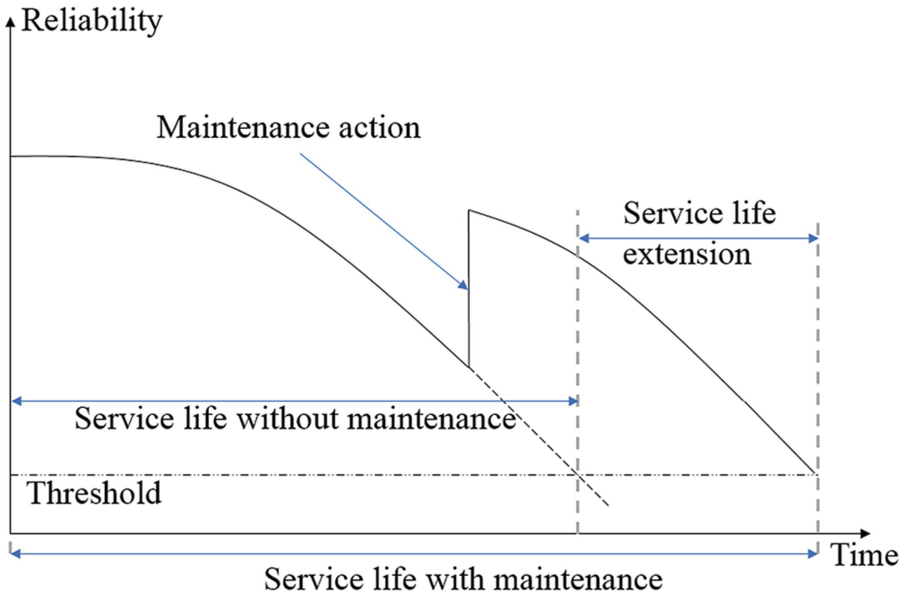
(Extracted from ISBN 0-7844-0578-6)

Design working life (Eurocode "0")

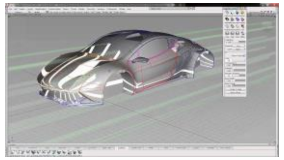
"*The* ***structure shall be designed*** *such that deterioration over its* ***DESIGN WORKING LIFE does not impair the performance*** *of the structure below that intended, having due regard to its environment and the anticipated level of maintenance.*"

Table 2.1 - Indicative design working life

Design working life category	Indicative design working life (years)	Examples
1	10	Temporary structures (1)
2	10 to 25	Replaceable structural parts, e.g. gantry girders, bearings
3	15 to 30	Agricultural and similar structures
4	50	Building structures and other common structures
5	100	Monumental building structures, bridges, and other civil engineering structures
(1) Structures or parts of structures that can be dismantled with a view to being re-used should not be considered as temporary.		



Durability - Complexity of phenomena



- Although **FRP composites have been successfully used** in the **automotive**, **marine**, **wind energy**, and **aerospace sectors**, there are critical differences where compared with **Civil Engineering applications** in terms of:
  - Loading conditions
  - Environmental conditions
  - Types of materials used
  - Processes

- A **huge variety** of different **constituent materials** are commercially available.

- In many situations, **there is an absence of standards** for the **characterization of the durability**.

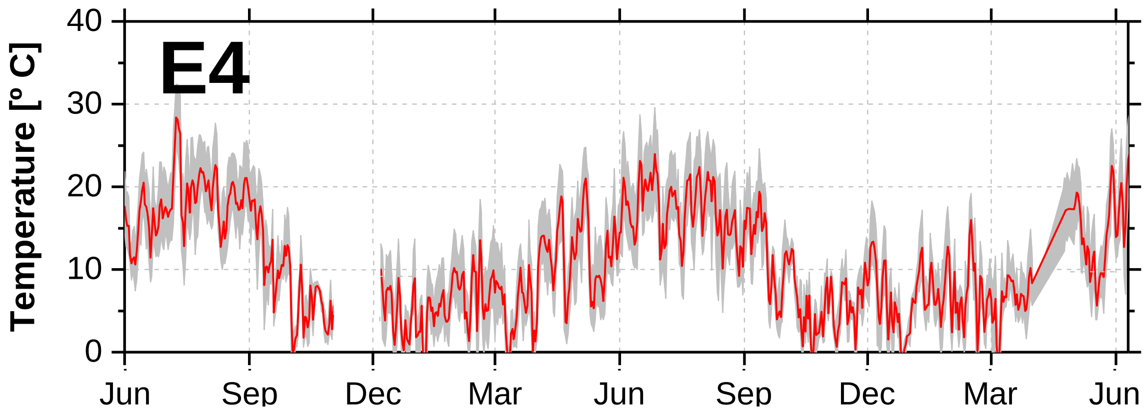
- Difficulties in testing: **artificial accelerated** *versus* **real/natural** aging.

Accelerated aging *vs*. real ageing

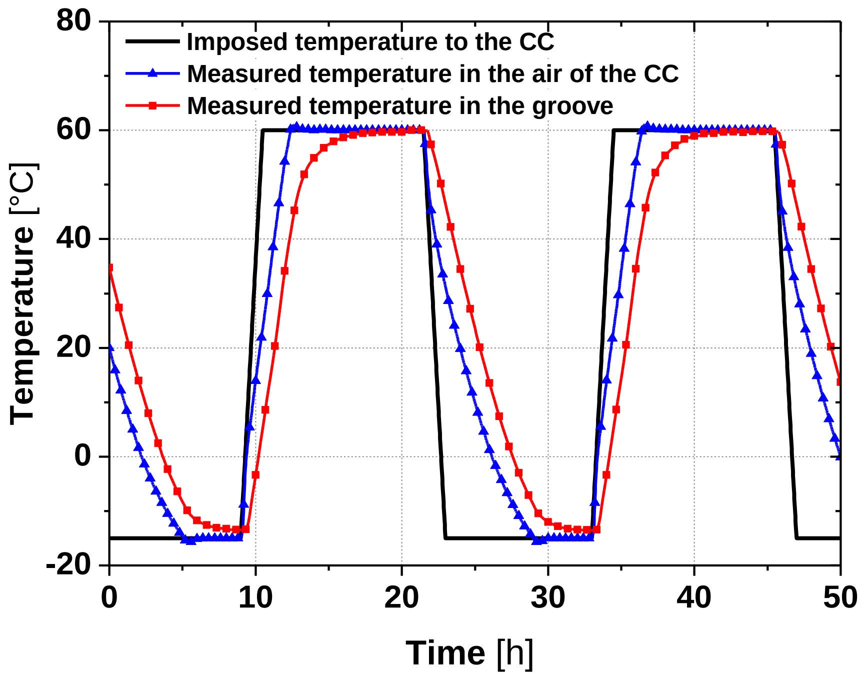
Artificial accelerated aging

Accelerated aging *vs.* real ageing

Natural Aging



Artificial Aging

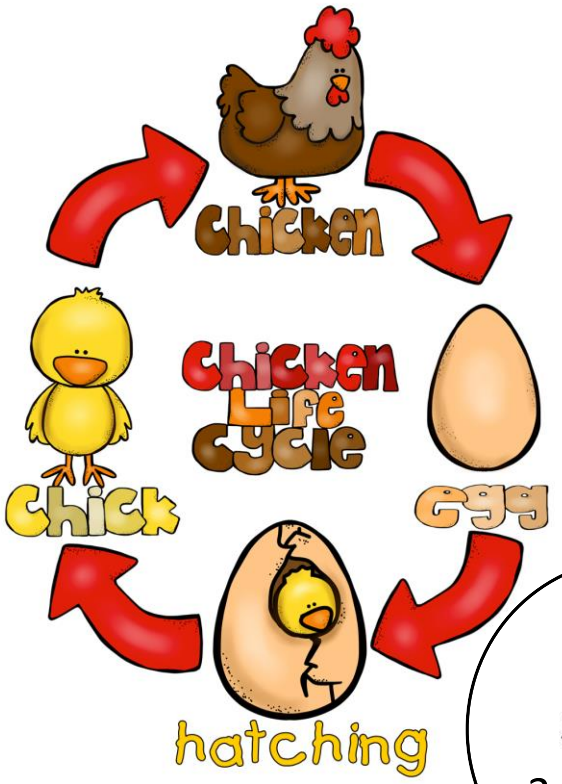


24 hours

Real aging *vs*. accelerated aging

(Real ageing tests)

REAL CHICKEN LIFE CYCLE



3 weeks at 38 °C

(Artificial accelerated ageing tests)

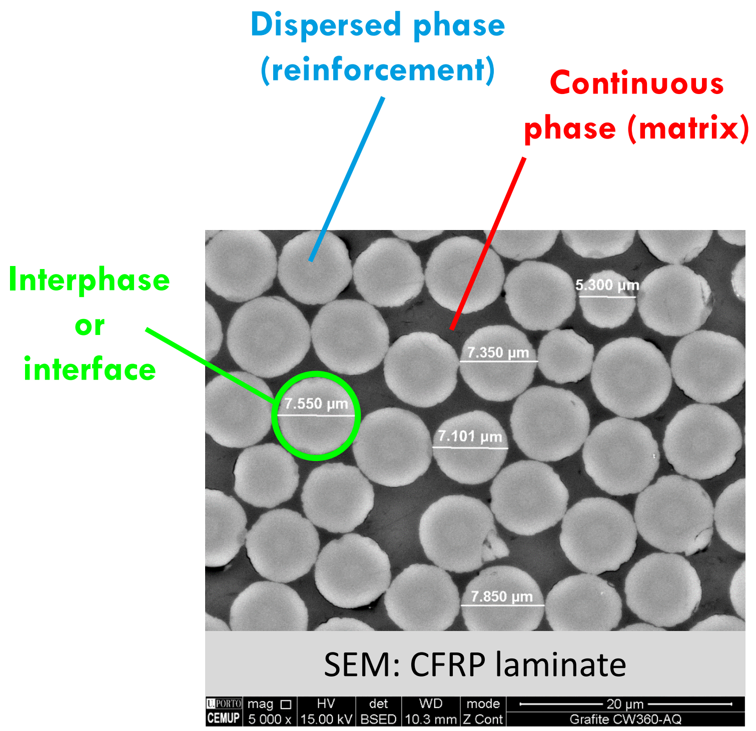
ACCELERATED CHICKEN LIFE CYCLE

- 2 weeks at 48 °C ?
- 1 week at 58 °C ?
- 1 day at 68 °C ?
- 1 hour at 78 °C ?
- 10 minutes at 100 °C!!!

Basic concepts: Parameters that influence the durability

The **durability and long-term behavior** of composite material, component or structure depends mostly on:

- Polymeric matrix: type of resin, additives and fillers
- Fibres: types of fibre(s), fibre content and layup, including surface veil
- Fibre-matrix interphase (or interface)
- Manufacturing process
- Production quality and resulting defects
- Structural details
- Installation/assemblage and quality control
- Special measures
- Maintenance



SEM: CFRP laminate

Source: CEN/TS 19101:2022 (E)

Basic concepts: Degradation factors *vs*. degradation mechanisms

- **Degradation factors** are all **agents** that act on the material, component or structure and that may **cause alterations on its performance**. The main degradation factors can be classified according to two categories:

Environmental degradation factors	Mechanical degradation factors
▪ **Thermal effects** ▪ **Moisture** ▪ **Chemicals** ▪ **UV exposure**	▪ **Static loading**: creep, relaxation ▪ **Dynamic loading**: fatigue, vibrations, impact

- **Degradation mechanisms** are characterized by a sequence of **chemical**, **mechanical** and/or **physical changes**, leading to the **alteration** of one or more **mechanical properties** of the material, component or structure **in a harmful way** when exposed to a degradation factor or a combination of them.

Thermal effects: Overview

- Normally, **thermal effects of composites** can be split in:
  - Service temperature conditions (below T_g* - 20 °C)
  - Thermal cycles
  - Sub-0 °C temperatures
  - Freeze-thaw cycles

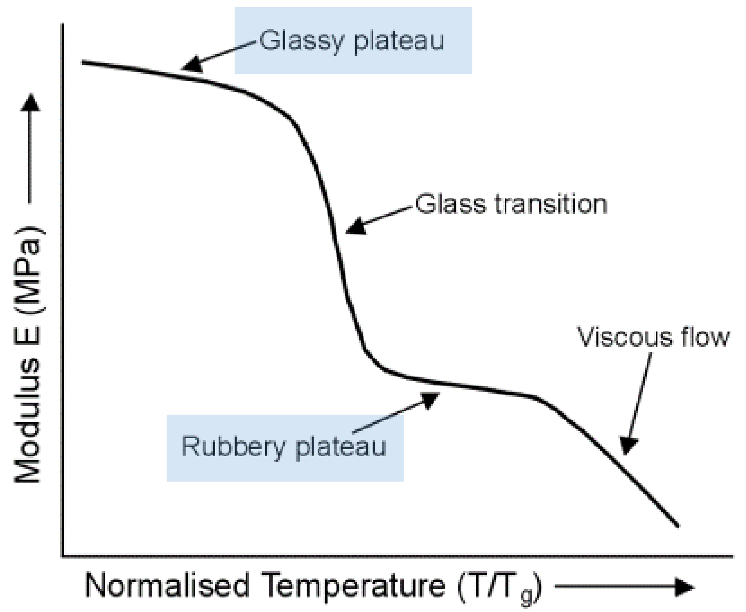
- In general, the **existing knowledge** on the thermal effects in FRP materials **is very limited**...

- Additionally, **test methods** adopted in the studies **vary significantly**, with respect to
  - the constituent materials (fibre and resin),
  - manufacturing processes,
  - type and exposure conditions and
  - characterisation techniques.

Thermal effects: What is glass transition temperature?

- **Glass transition temperature** (T_g) is the **temperature range** where the polymer substrate changes from a **rigid glassy material** to a **soft** likely **rubber** (not melted) material, and is usually measured in terms of the stiffness, or modulus.

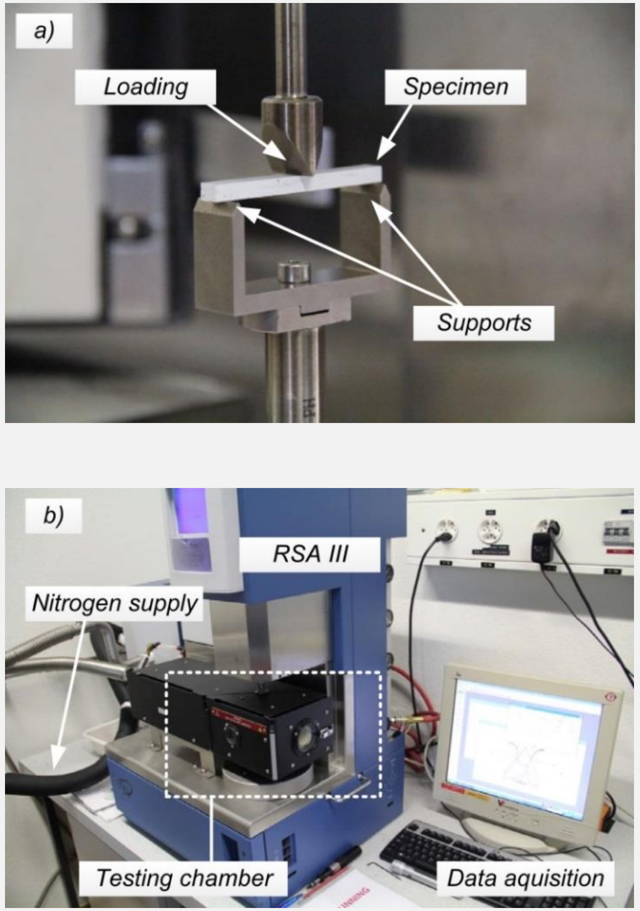
- By **cooling the adhesive** from temperatures **above** T_g to temperatures **below** T_g result into **a full recovery of its mechanical properties**.

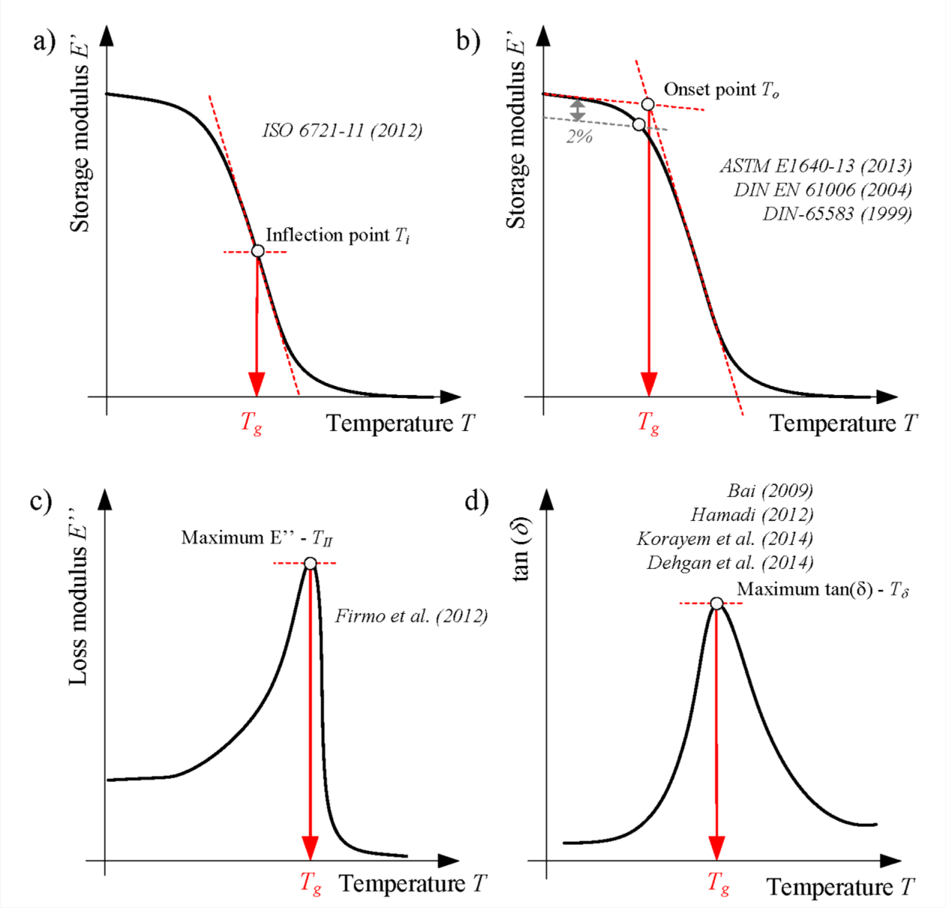


Techniques for assessing the T_g:

- **D**ifferential **S**canning **C**alorimetry (DSC)
- **T**hermal **M**echanical **A**nalysis (TMA)
- **D**ynamic **M**echanical **A**nalysis (DMA)

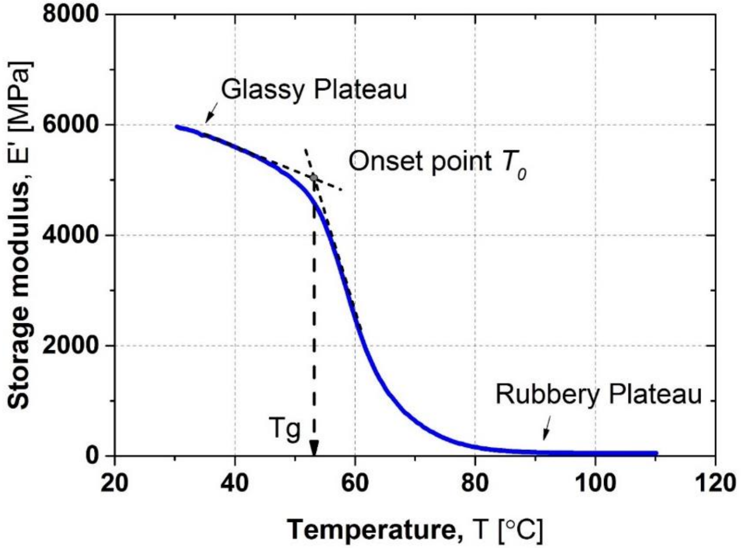
Thermal effects: Dynamic Mechanic Analysis





(***Michels et al. 2015***)

Example of a DMA test of an epoxy adhesive



Thermal effects: Effects on the matrix

- **Glass transition temperature of resins:**
  - Polyester resins → 70 °C to 95 °C
  - Vinylester resins → soften above 90 °C
  - Cold curing epoxy resins → 50 °C to 70 °C
  - Epoxy adhesive systems with high T_g → 230 to 260 °C

- **Sub-zero** and **extreme low temperatures** can cause **polymer matrix embrittlement**, which increases its strength and stiffness → **more brittle failure mode**.

- **Low temperatures** can also cause **matrix hardening** and **matrix micro-cracking**.

- **Freeze-thaw** with the presence of **salts and moisture** can **accelerate the degradation ratio**, throughout the expansion of salt deposits and swelling.

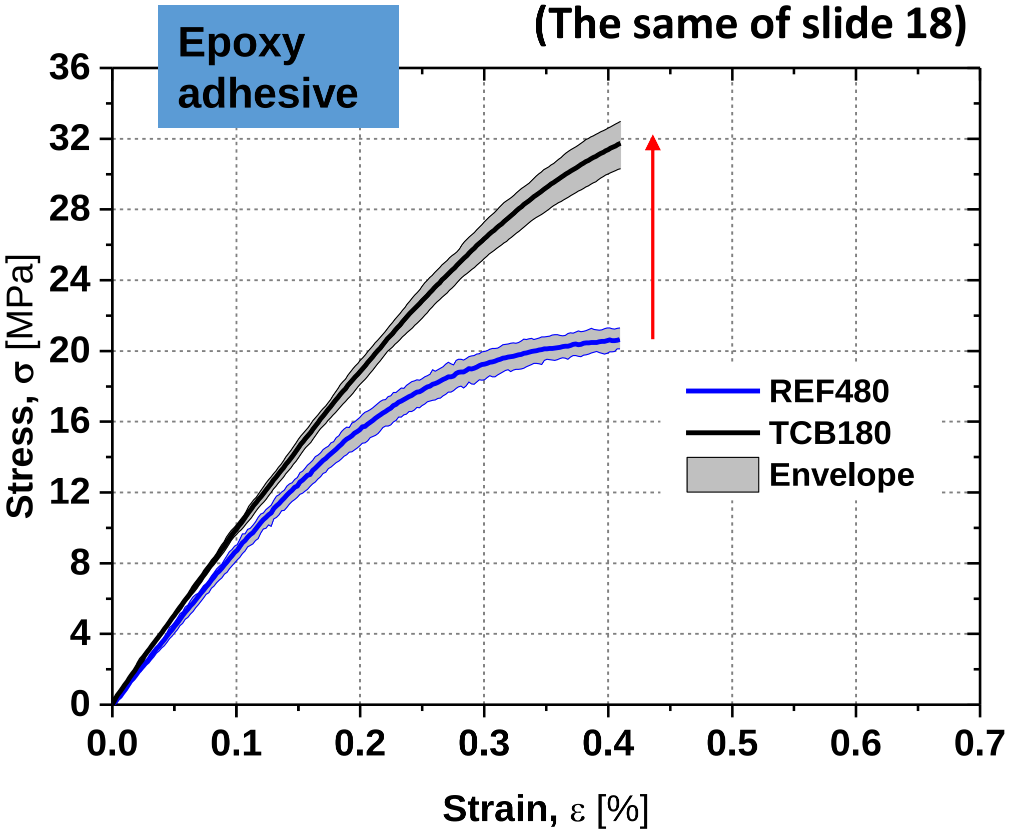
Thermal effects: Effects on the matrix

- **Post-curing** occurs when a polymer material is submitted to a **temperature higher** than the one at the **first cure**, thus increasing the curing degree (*). Normally, the **post-curing** phase increases the **mechanical properties of the material**.

- **Post-curing** is observed when the **temperatures** in the polymer material temporally **exceed the T_g**. T_g also **increases** with **post-curing**.

(*) The curing degree describes the conversion rate achieved during crosslinking reactions (curing). In macromolecular chemistry, crosslinking refers to reactions in which a large number of individual molecules are linked to form a three-dimensional network. Linkage can be achieved either by direct setup of macromolecules or reaction to the already existing polymers.

(The same of slide 18)



f_{epoxy} ↗ +58%

E_{epoxy} ↗ +24%

Thermal effects: Effects on the interphase

- **The coefficient of thermal expansion** (CTE) are typically lower in the fibres than in matrix of FRP materials.

- **Sub-zero** and **extremely low temperatures** can cause **embrittlement of the matrix** and **reduce** the **effectiveness of stress transfer** between the matrix and the fibres.

- **Freeze-thaw** cycles might cause **thermal stresses** (due to differential CTE between fibre and matrix) and, along with the **embrittlement of the matrix**, can result in the **matrix microcracking** and on the **development of residual stresses** which could initiate the **debonding of fibres** from the polymer matrix.

- **Elevated temperatures** can result in thermal gradients and, together with **increased viscoelasticity**, would result in the **degradation of the fibre-matrix interface**.

Thermal effects: Effects on the fibres

- **Fibres** are typically **immune** to **temperature effects**!

- Nevertheless, the exposition of **GLASS** and **ARAMID** FRP to “normal” service temperatures (between -20 °C and 60 °C) lead to a **slight reduction** on the **elastic modulus**.

Thermal effects: Effects on FRP composite materials

- **Exposure to elevated temperatures** led to **reduction** on the **strength** and **stiffness** when approaching T_g of the polymer matrix. For **FRP composites** in civil infrastructures T_g ranges:
  - General cases: 65 °C - 120 °C
  - Pultruded composites: ≈140 °C.

- **Elevated temperatures** might result in the **chemical decomposition of the matrix**, degradation of the composing fibre (oxidation of carbon or softening/melting of glass fibres) and fibre-matrix interface damage due to incompatible thermal expansion.

- **Post-curing of the polymer matrix** may occur after thermal exposure with **beneficial effects**.

- **Sub-zero temperature** and **freeze-thaw cycles** can **damage the FRP performance**, namely by **reducing its mechanical properties**.

Thermal effects: Mitigation measures

- **To avoid** undesired FRP **degradation**, the following aspects should be considered:
  - **Fibres** should be **completely** and well **covered by resin**;
  - **FRP** should **not** have **cracks**, either on the surface or in throughout thickness;
  - **FRP** should **not** have **voids**;
  - The **production** process should **guarantee good cure of the resin**;
  - **Good compatibility** in terms of **coefficient of thermal expansion** (CTE) between **matrix** and **fibres**.

Moisture

- **Moisture** includes direct contact to rain, humidity, moisture, immersion in aqueous solutions, among others...
- Moisture causes **changes** in the **physical**, **mechanical** and **chemical** properties of composites.
- **Physical ageing** refers to **reversible changes** of physical material properties.
- **Chemical degradation** causes mostly **irreversible changes** in chain scission and may also affects the interfacial bond and effects at the fibre level.

Moisture: Main degradation mechanisms

Classification	Degradation Mechanism	Location			Reversibility
		Fibre	Matrix	Interface	
Physical	Plasticization		X	X	Yes (*)
	Swelling		X		Yes (*)
	Relaxation		X		No
Chemical	Hydrolysis				No
	Chain Scission		X		No (*)
	Pitting	X			No (*)
	Debonding			X	No (*)
	Leaching	X	X	X	No

(*) Sometimes is reported as both irreversible and reversible.

Moisture: Plasticization, swelling and relaxation

- **Plasticization** is the incorporation of low-molecular weight molecules into a polymer network that may act as a diluent or plasticizer. *This physical mechanism occurs **without increasing the specific volume**, since incorporated **molecules fill the empty voids** between the polymer macromolecules.*

- **Swelling** describes volumetric changes due to moisture content alone (independent of thermal expansion). *The **swelling volume** increase **in polymers** is usually **lower than** the **volume of water absorbed**. This is due to the fact that when water is absorbed by a polymeric material, the comparatively small water molecules must either occupy the free volume as described above (plasticization) or cause these swelling effects.*

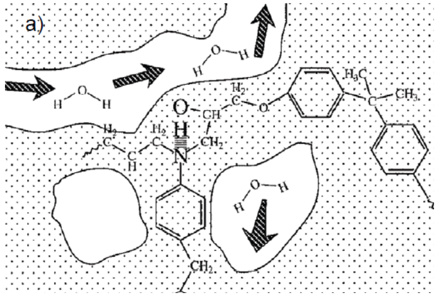
- Polymer **relaxation** comprises the redistribution of the voids and free volumes in the polymer network due to swelling effects caused by penetrant molecules, forcing macro-molecular movement - through relaxation, more moisture content can be absorbed in the polymer.

Moisture: Hydrolysis and leaching

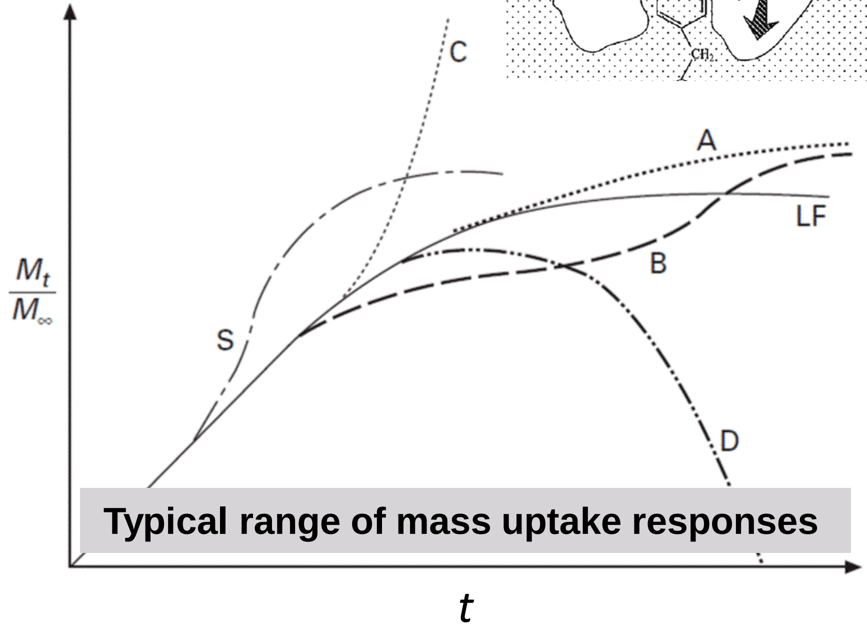
- **Hydrolysis** typically occurs through the hydrolytic molecular bond cleavage due to exposure to moisture or water molecules, resulting in the formation of water soluble fragments.

- **Leaching** results i) from water acting as percolating fluid and promoting the extraction of low molecular weight degradation products from the polymer matrix or ii) due to the initial polymerization reaction and cure that may also leached out the low molecular weight segments, resulting in an apparent weight loss of the polymer. This effect is especially critical at elevated temperatures.

Moisture: Water uptake in FRP composite materials



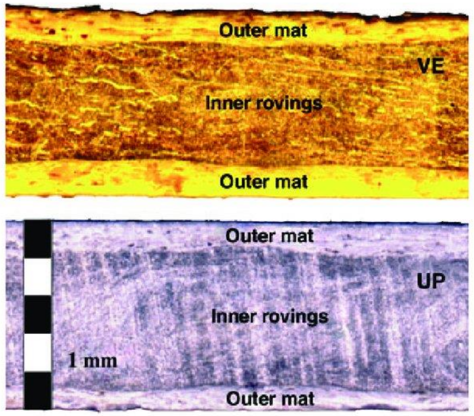
- The <u>penetration of moisture</u> into polymeric resins, FRP composites materials or adhesives occurs either by **diffusion** or **capillarity**, through an activated absorption/diffusion process:
  - **Fickian** by direct diffusion through the <u>polymeric matrix</u>;
  - **Non-Fickian** by diffusion through <u>existing voids or cracks in the matrix</u>;
  - **Capillary** by wicking along fibre-matrix interfaces.



Typical range of mass uptake responses

- Several studies have shown that the **saturation level depends on the immersion media**, typically with **higher** saturation levels are achieved in:
  - **distilled water** >> **fresh water**
  - **fresh water** >> **salt water**

Moisture: Effects on resins



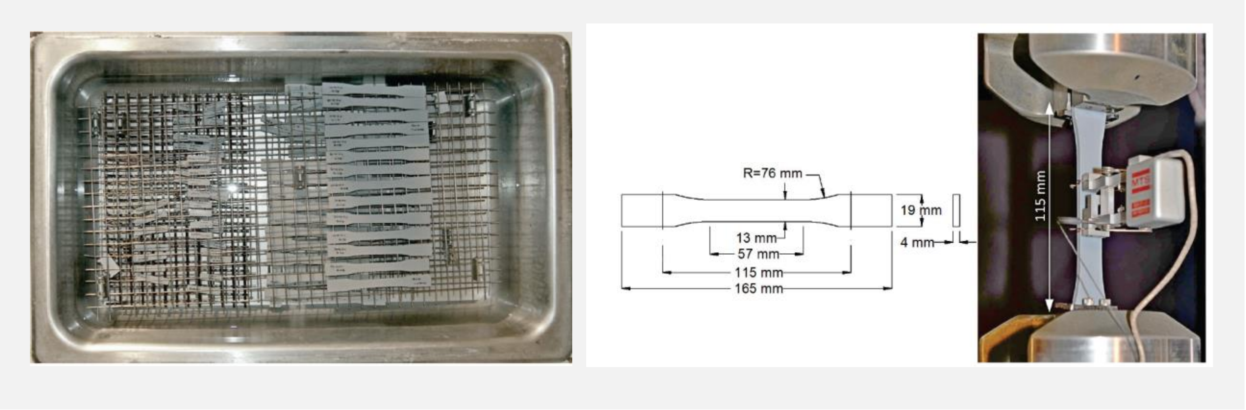
- **POLYMERIC RESINS** are the **most sensitive constituent** of composites to **moisture**!

- **VINYLESTER RESINS** are usually less susceptible to hydrolysis when compared to **unsaturated polyester resins** (due to their terminal ester functional groups, which are shielded by methyl groups).

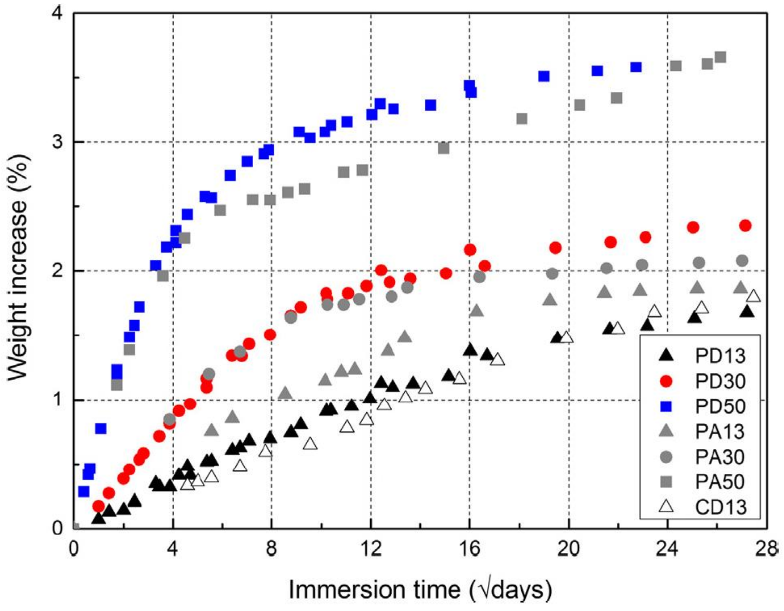
- At early stages water penetration in **THERMOSETTING POLYMERS** causes **physical ageing** takes place, mainly **plasticization**.

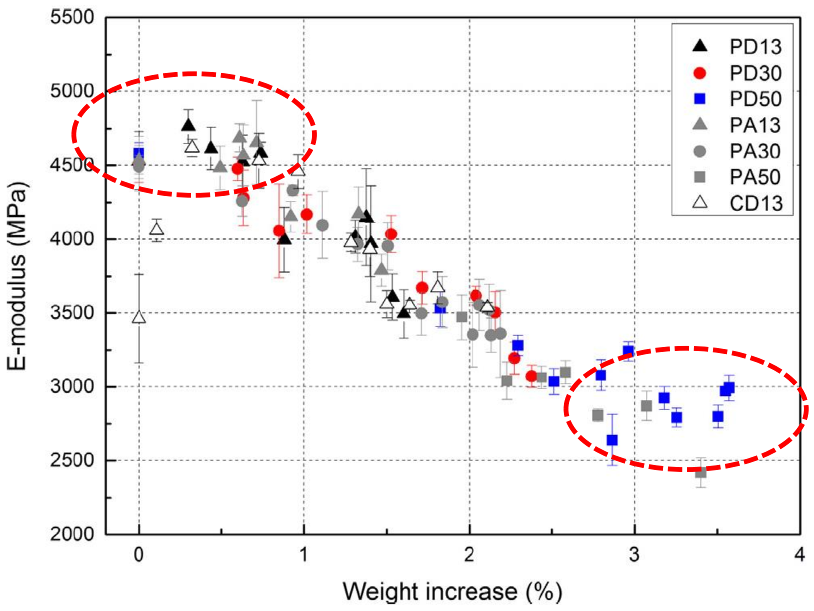
- For longer periods of water exposure, **chemical ageing** simultaneously occurs due to **hydrolysis**, involving the **chemical attack** on the ester linkages of the polymer (in polyester and vinylester resins).

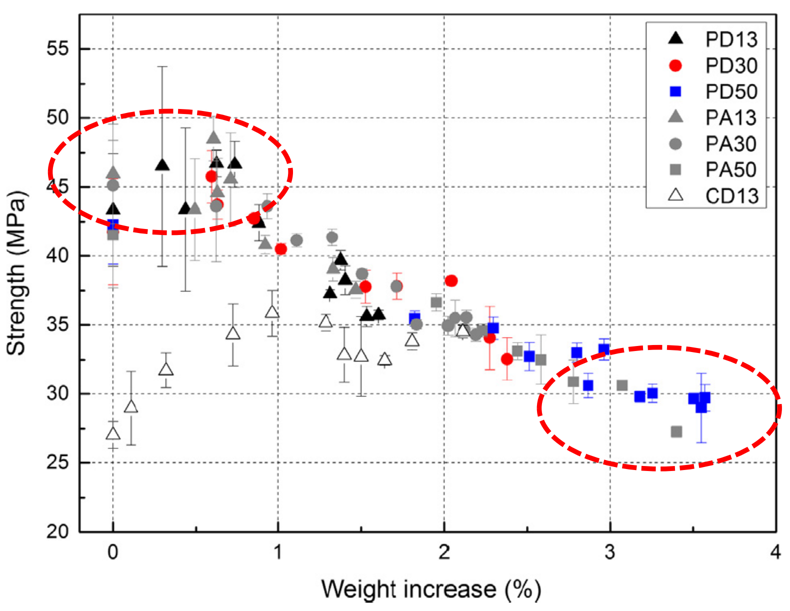
Moisture: Effects on resins



Example of an epoxy adhesive: Sikadur 330



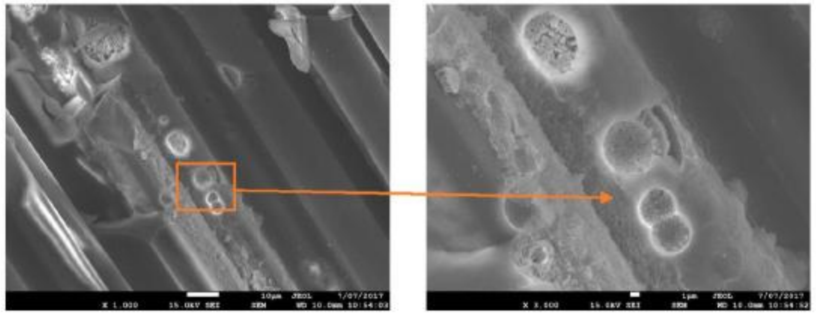




Source:

- *Savvilotidou, M.; Vassilopoulos, A.P.; Frigione, M.; Keller, T. (2017) "Development of physical and mechanical properties of a cold-curing structural adhesive in a wet bridge environment." Construction and Building Materials, 144: 115–124.*

Moisture: Effects on the GLASS fibres



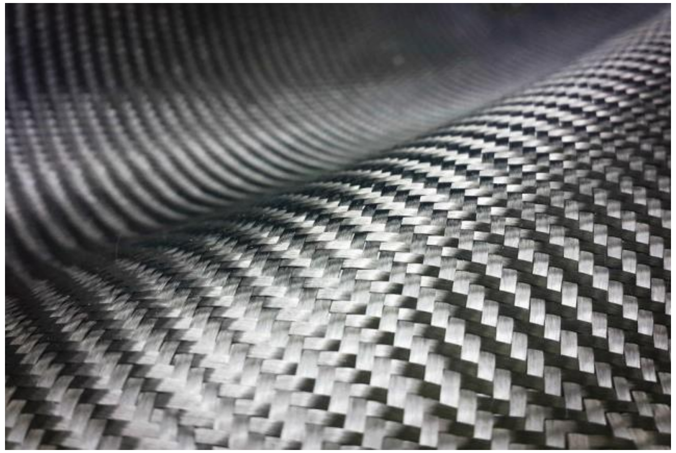
- **Steps of degradation**:
  1. Moisture **extracting ions** from the fibres ➔ Fiber structure is altered.
  2. Creation localized **cavities** in a localized area **damaging the fibre surface** (due to the of the ions with water, which pit the fibre surface) ➔ may result in **flaws that significantly degrade strength**, and can result in premature fracture and failure of the fibres.

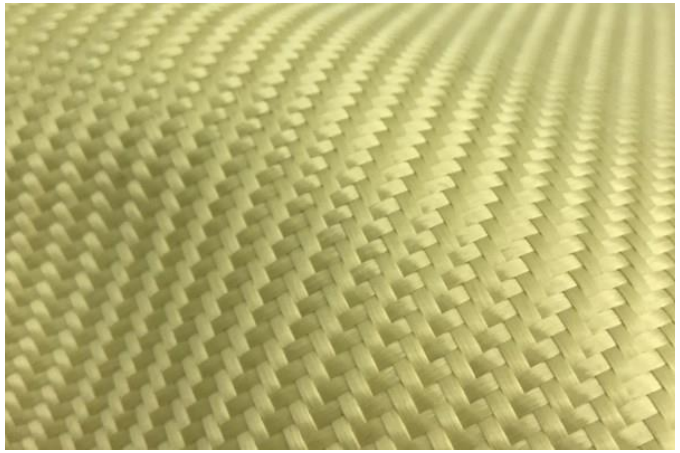
- **Different approaches** have been proposed to **explain the stress corrosion** of glass fibres due to water:
  - **Moisture adsorption** results in a decrease in the surface energy of glass fibres, thus reducing the cohesive strength of the material;
  - The reduction of glass fibres strength due to **moisture exposure** is caused by the slow growth of cracks until a critical size is reached leading to failure;
  - **Hydrolysis** and ion exchange reactions occur in structural flaws, ultimately causing fibre failure.

Moisture: Effects on the Carbon/Aramid fibres

- **CARBON FIBRES** are relatively **resistant to degradation** in the presence of water.

- **ARAMID FIBRES** can absorb significant amount of moisture (up to 4.5% w/w); due to their aromatic amide structure, **aramid fibres are prone to hydrolysis** in their amorphous regions.





Moisture: Effects on FRP composite materials

- **Mechanical properties of FRP materials** can be significantly affected by the presence of **moisture**, as a result of the degradation of the matrix, the fibres and the interphase.

- **Degradation of FRP materials** is generally **less sensitive** when compared to that experienced by the corresponding neat resins due to the presence of the fibre reinforcement.

- **Reductions** in **longitudinal and transverse tensile**, **compressive**, **shear** and **flexural properties** due to moisture exposure are frequently reported in the literature.

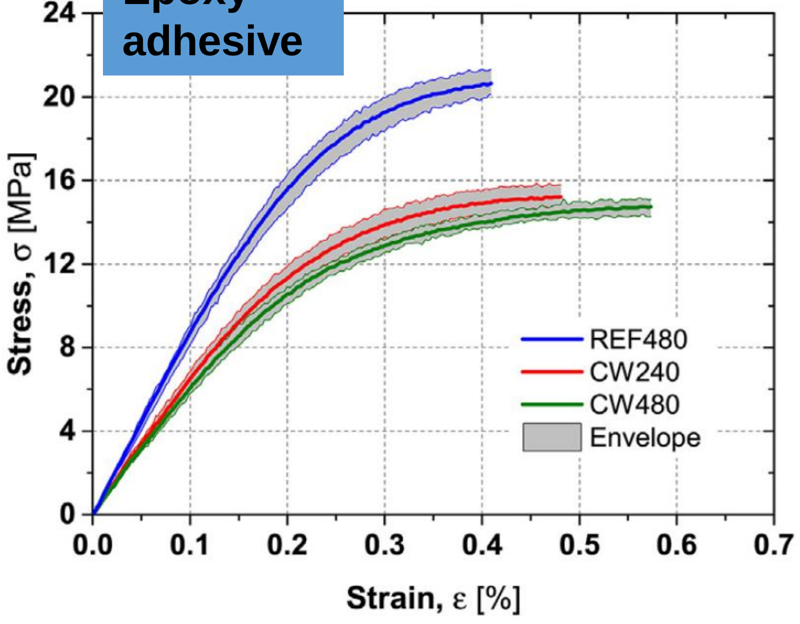
- Effects of moisture-related degradation are **more significant** for **strength** than for **stiffness**, with changes in modulus generally being very small (typically in the order of 10% over a period of 10-15 years).

- Since the **polymer matrix is more sensitive to moisture** than the **reinforcing fibres**, **matrix dominated properties** are typically more **affected** than fibre dominated properties.

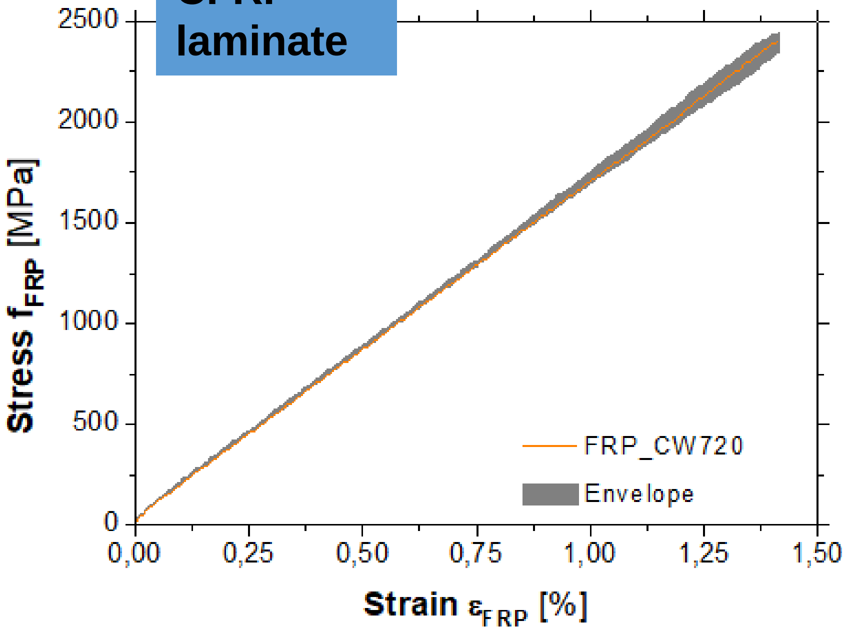
Moisture: Example of epoxy adhesive *vs*. CFRP laminate

Up to ≈2 years of ageing!

Epoxy adhesive



CFRP laminate



f_{epoxy} ↘ **-28%**

E_{epoxy} ↘ **-35%**

f_{CFRP} ↘ **-7%**

E_{CFRP} ↘ **-1%**

Source:

- *Silva, P.; Fernandes, P.; **Sena-Cruz, J.**; Xavier, J.; Castro, F.; Soares, D.; Carneiro, V. (2016) "Effects of different environmental conditions on the mechanical characteristics of a structural epoxy." Composites Part B: Engineering, 88: 55–63.*
- *Fernandes, P.; Silva, P.; Correia, L.; **Sena-Cruz, J.** (2015) "Durability of an epoxy adhesive and a CFRP laminate under different exposure conditions", SMAR2015 – Third Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, September 7th – 9th, Antalya, 8 pp.*

Moisture: Mitigation measures

- The strategies **delay degradation** of FRP composite materials against **moisture** include:

  i. **Proper material selection** and **quality control** during **processing**;

  ii. Depending on the aggressiveness of the exposure, the **moisture ingress** into the FRP material can be delayed through the **use of protective coatings**, namely **gel coats** and **coatings**.

Chemicals: Overview

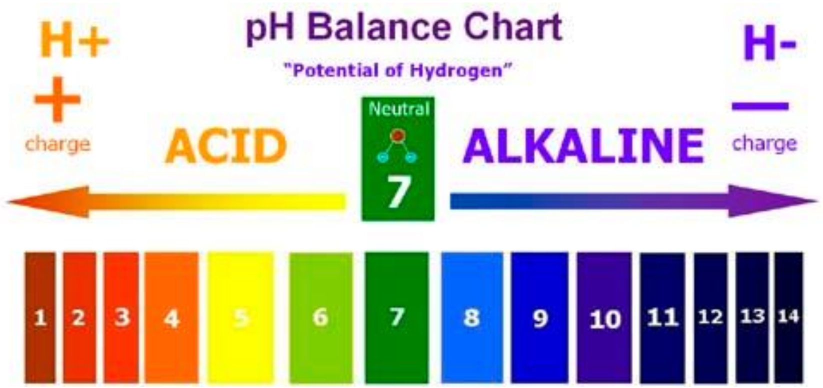
- **FRP composite materials** have been **successful used in aggressive chemical environments**, in a **wide range of sectors of the chemical industry** (such as water treatment, paper, food processing, pharmaceutical power generation) for the last **50 years**, as **chemical-resistant materials** (particularly **GFRP**).

- **FRP composite materials** (particularly **CFRP**) have also been used in the **aerospace industry** for many years, and with an extensive research related to the chemical resistance.

- However, as explained before, there are **critical differences** where these sectors are compared with **Civil Engineering** applications.

- **Specifications** of FRP composite materials for civil-engineering applications requiring **chemical resistance still does not exist**!

Chemicals: Effects on resins



- **POLYESTER RESINS** in general have **good acid resistance**. **Isophthalic resins** have a **better** chemical resistance than **orthophthalic resins**. **Unsaturated polyesters** can be also formulated for **high resistance** to **acids** and **weak alkalis**.

- **EPOXY RESINS** are **highly resistant** to **water** solutions, **organic solvents** and **alkaline environments**, and they can be formulated for **better resistance to several chemicals**.

- **VINYLESTER RESINS** combine the properties of both **unsaturated polyester** and **epoxy resins**, providing an **excellent resistance** to **water** solutions, **organic solvents** and **alkaline environments**.

Chemicals: Effects on fibres

- GLASS FIBRES, by default, are **damaged by alkaline environments** and are susceptible to **stress corrosion cracking**. Due to that, glass fibres are chemical improved depending on the type of need:
  - C-glass: High chemical resistance glass fiber
  - AR-glass: Alkali resistance glass fiber
  - CR-glass: Acid corrosion resistance glass fiber

- ARAMID FIBRES are **chemically stable** under a wide variety of chemicals; however, certain strong acids and bases can cause degradation (particularly over long periods of exposure and at elevated temperature).

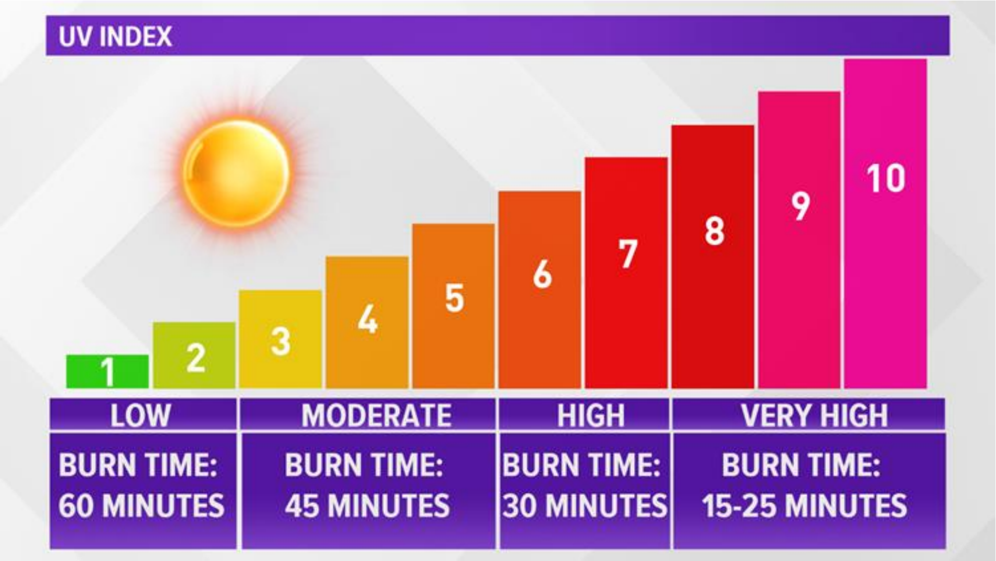
- CARBON FIBRES are by nature **chemically inert to most environmental conditions**. In general, they are **not affected** by solvents, bases and weak acids.

Chemicals: Effects on FRP composite materials

- Until now, **there are no standard test methodologies** for assessing the **chemical resistance** of FRP composites utilized in Civil Engineering.

- The **right choice** of the FRP composite materials should be done based on:
  - the particularities of the chemical environment;
  - the service temperatures;
  - the exposure profile;
  - the existence of synergistic effects.

UV exposure: Overview



- **Outdoor** FRP structures can be exposed to the ultraviolet (UV) radiation from the sun.

- **UV radiation** affects mainly the **polymer matrix** of FRP materials. This may yield to **detrimental** in the overall mechanical properties of FRP composite materials.

- Results show that the **effects** of exposure of **FRP composite materials** to **UV radiation** on are usually **confined to the top few microns of the surface**, affecting especially their aesthetical properties: **loss of gloss** and **discolouration**.

- However, when the **severity is high**, additional problems may occur:
  - stress concentrators and initiate fracture at much lower stress levels;
  - ingress of moisture.

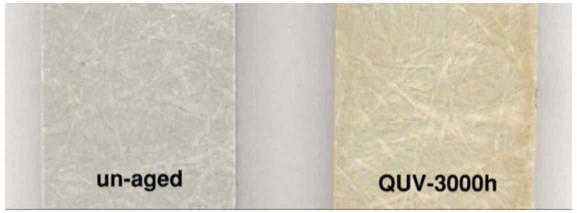
UV exposure: Effects of the matrix

- Most commercial **polymers are susceptible to photodegradation** caused by the **UV component** of solar radiation, because they have <u>bond dissociation energies with wavelengths matching those of UV radiation</u> (295 to 400 nm).

- Depending on the **type of polymer** and long periods of exposure other damage my occur, namely:
  - Crosslinking and rearrangement processes;
  - Surface crazing;
  - Branching;
  - Chain scission;
  - Cracking formation.

UV exposure: Effects of the on FRP composite materials

- **UV-induced degradation** in FRP composite materials typically occurs according to the following sequence:
  - Loss of surface gloss;
  - Surface discoloration;
  - Chalking;
  - Flaking of surface resin;
  - Pitting;
  - Microcracking;
  - Blistering;
  - Severe loss of resin from outer surface, fibres not yet visible;
  - Severe loss of resin from outer surface, fibres visible (blooming);
  - Fibres visible and loosened from the surface;
  - Delamination of topmost ply.



Loss of surface gloss and surface discoloration

Fibre blooming

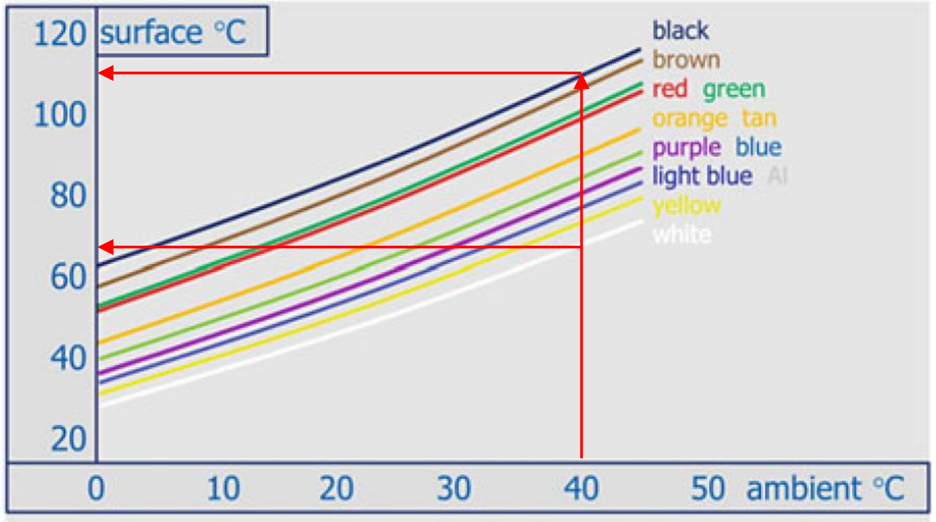
UV exposure: Mitigation measures

- The strategies **delay photodegradation** of FRP composite materials against **UV exposure** include:

  i. Introduction of **stabilizers** into the polymer matrix:
     - Controlling the amount of radiation reaching the polymer
     - Inhibiting chemical reactions started by radiation absorption

  ii. Application of **surface protections** of the FRP components, namely **gel coats** or **appropriate paints**.

The effect of direct sunlight on the surface temperature of different coloured objects



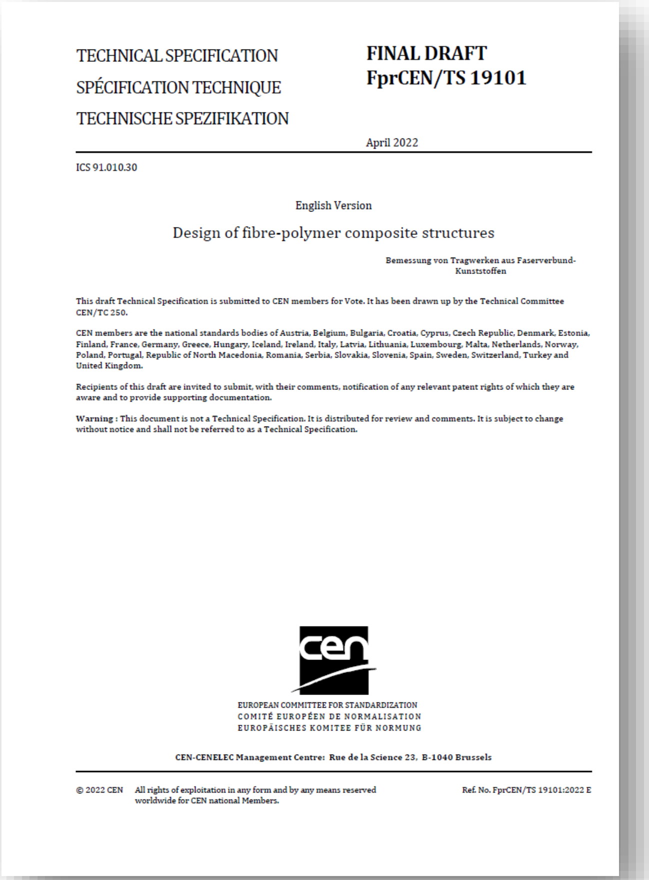
Source: P. Davies, Y.D.S. Rajapakse. Durability of Composites in a Marine Environment, Springer, 2014.

How durability is addressed in the Codes?

CEN/TS 19101:2022 - Design of fibre-polymer composite structures

- ❑ Basis of design
- ❑ Materials
- ❑ Durability
- ❑ Structural analysis
- ❑ Ultimate limit states
- ❑ Serviceability limit states
- ❑ Fatigue
- ❑ Detailing
- ❑ Connections and joints
- ❑ Annex A (Informative) Creep coefficients
- ❑ Annex B (informative) Indicative values of material properties for preliminary design
- ❑ Annex C (normative) Buckling of orthotropic laminates and profiles
- ❑ Annex D (normative) Structural fire design
- ❑ Annex E (informative) Bridge details

LAMINATES
PROFILES
SANDWICH PANELS



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ICS 91.010.30

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Design of fibre-polymer composite structures

Bemessung von Tragwerken aus Faserverbund-Kunststoffen

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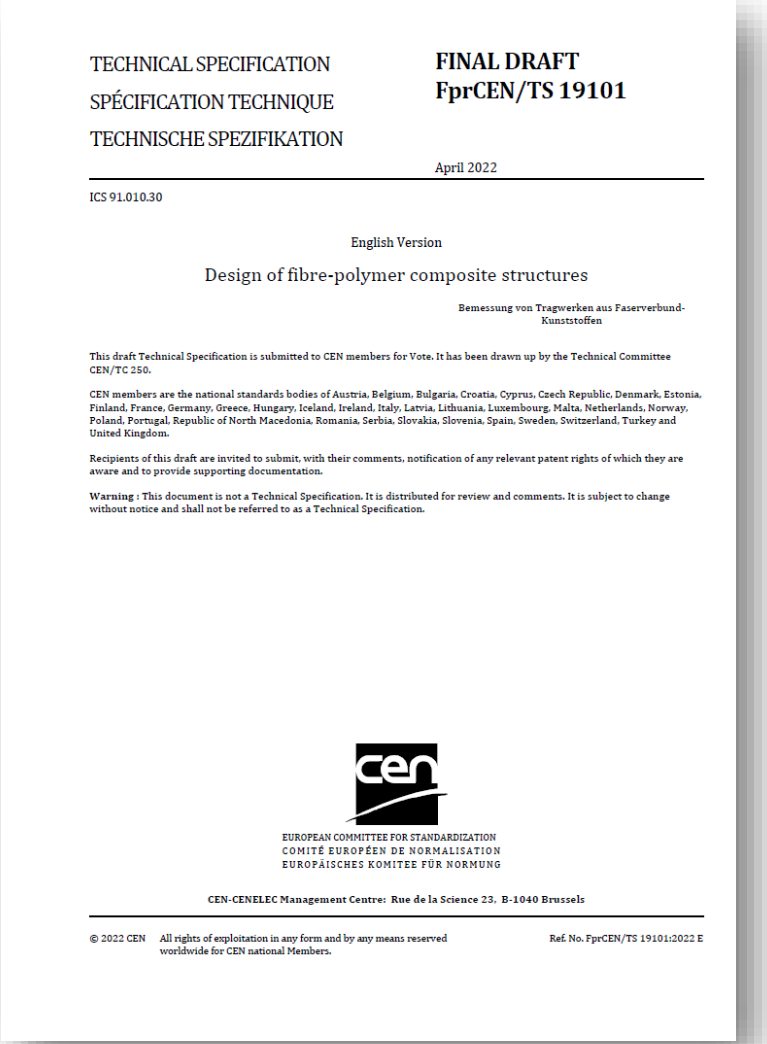
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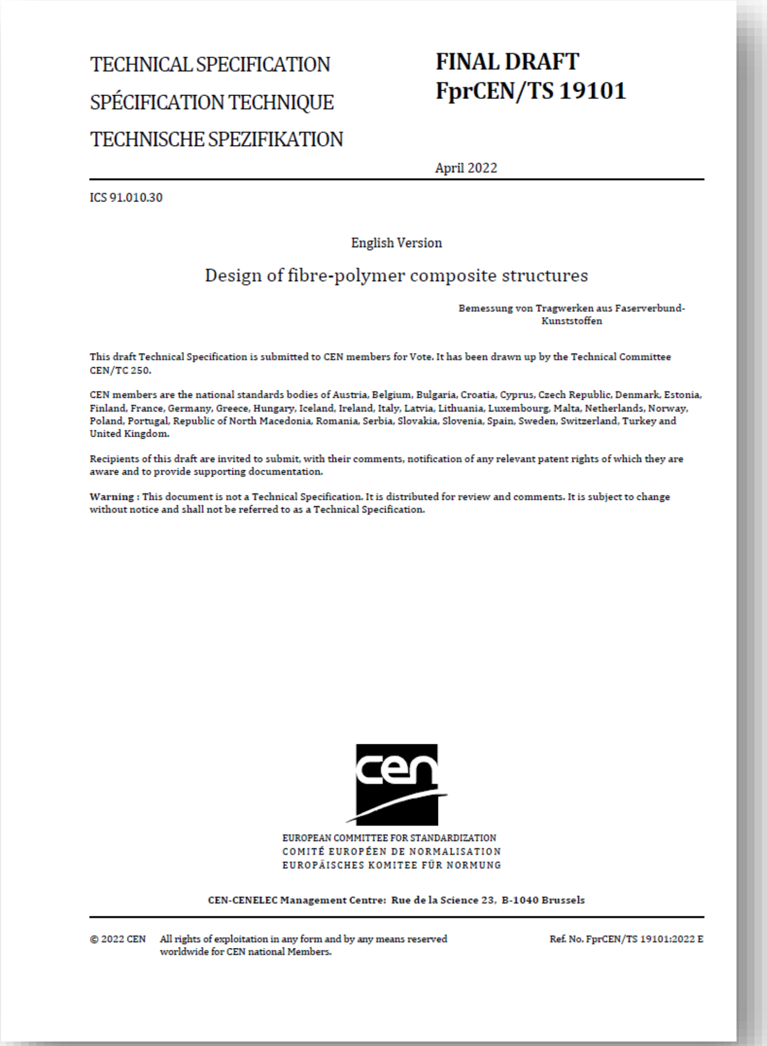
- **Ultimate limit states (*ULS*):**

$$E_d \leq R_d$$

Design value of
EFFECT OF ACTIONS

Design value of the
RESISTANCE

How durability is addressed in the Codes?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- **Ultimate limit states (*ULS*):**

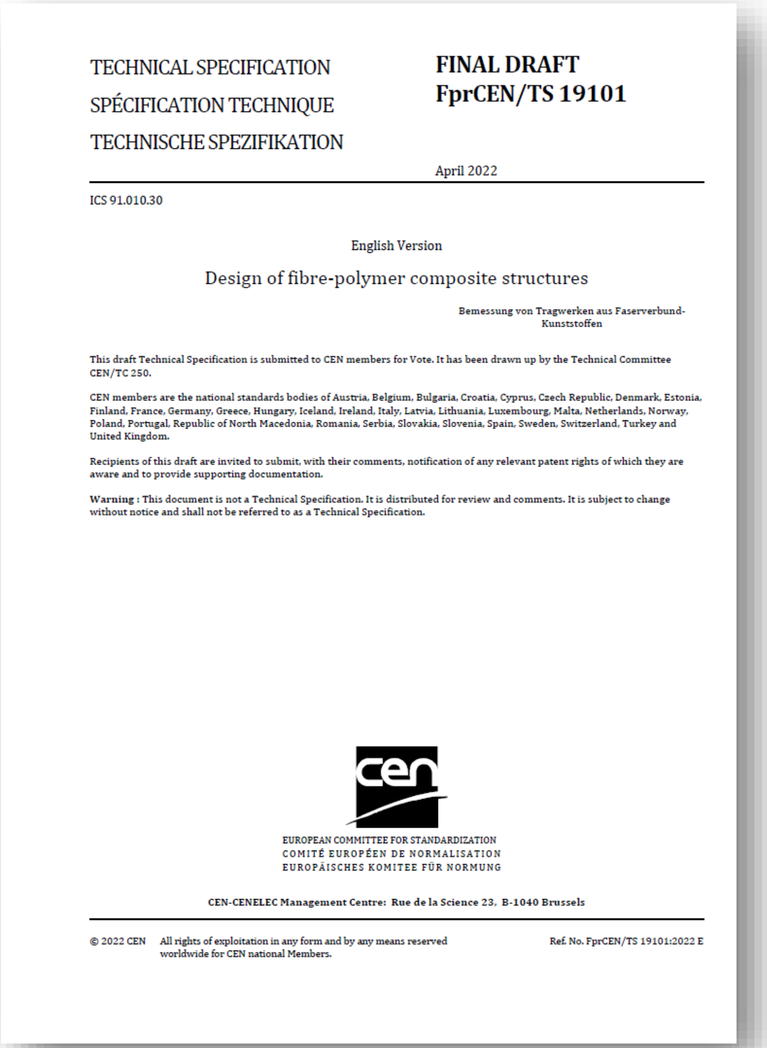
Composite components, and members, bolted connections and joints

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

Creep rupture, fatigue, adhesive connections, and fire

$$R_{\mathrm{d}} = R\left\{\eta_{\mathrm{c},i} \cdot \frac{X_{\mathrm{k},i}}{\gamma_{\mathrm{M}}}; a_{\mathrm{d}}; \sum F_{\mathrm{Ed}}\right\}$$

How durability is addressed in the Codes?



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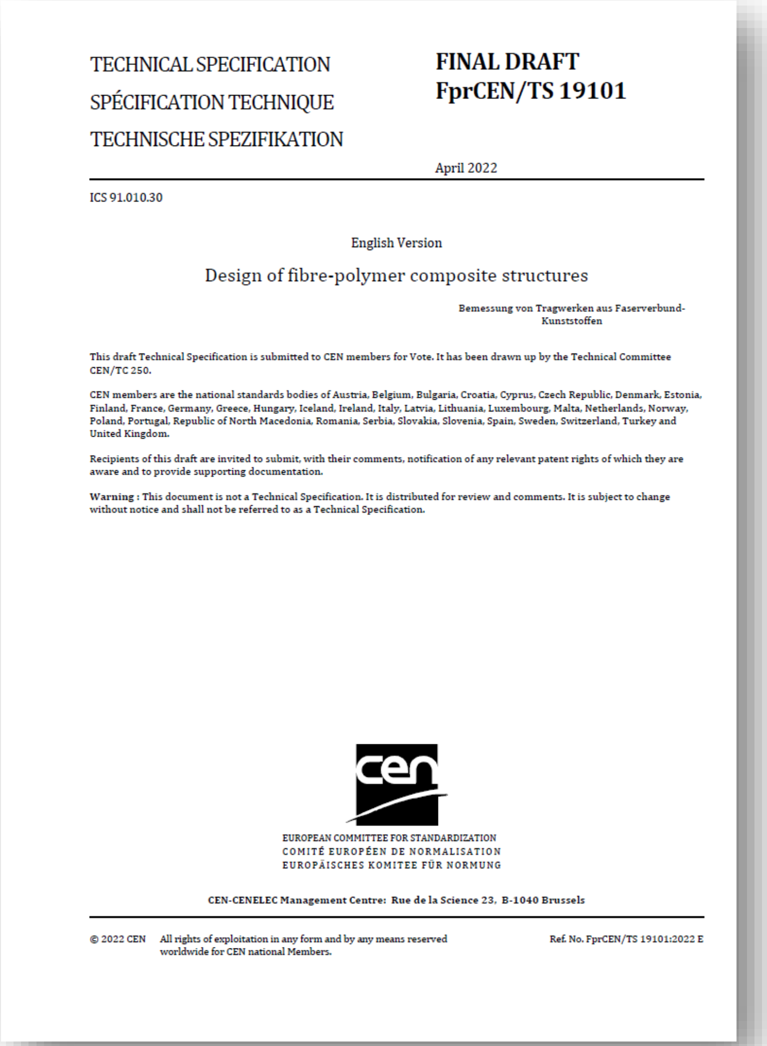
The **changes in the mechanical properties of composite materials**, **sandwich core materials** and **adhesives**, due to **temperature and moisture effects** through the **conversion factor**, η_c, given by:

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

Conversion factor for **temperature effects** (η_{ct})

Conversion factor for **moisture effects** (η_{cm})

How durability is addressed in the Codes?



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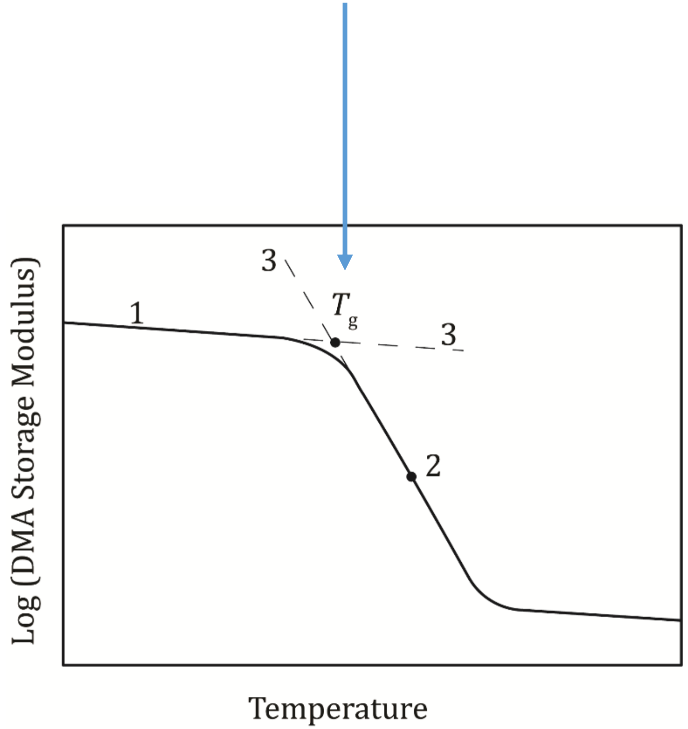
The TS limits the **maximum material temperature in service conditions**, T_s, in members, joints and components:

$$-40\,°C < T_s < T_g - 20\,°C$$



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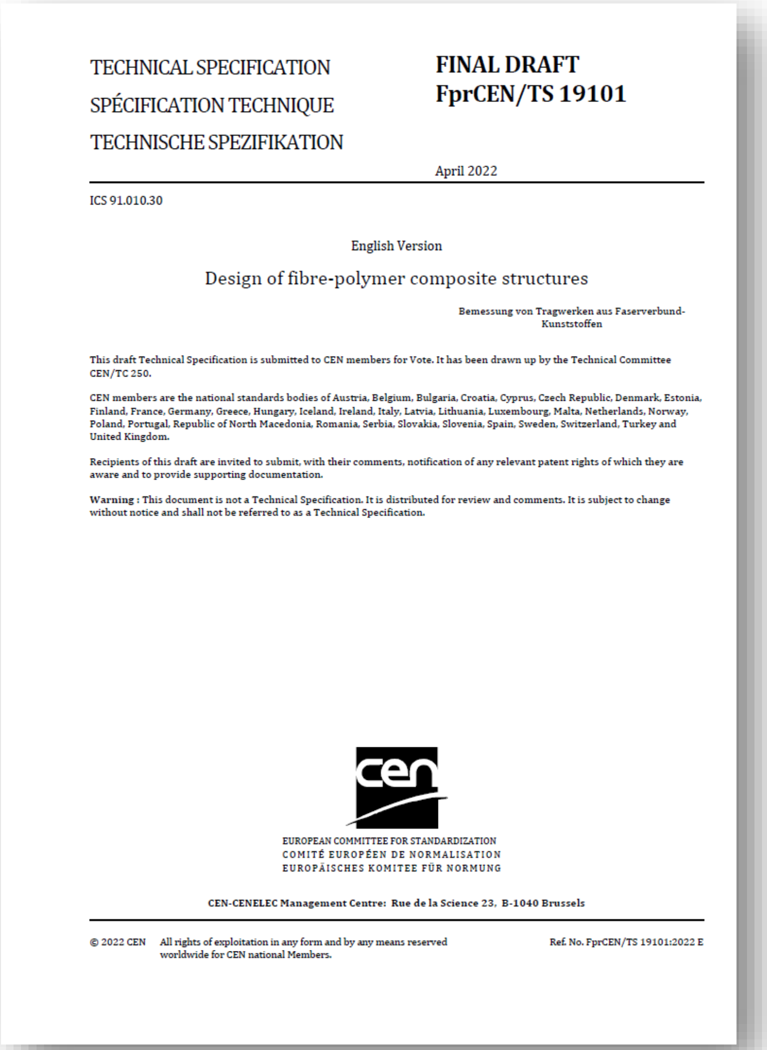

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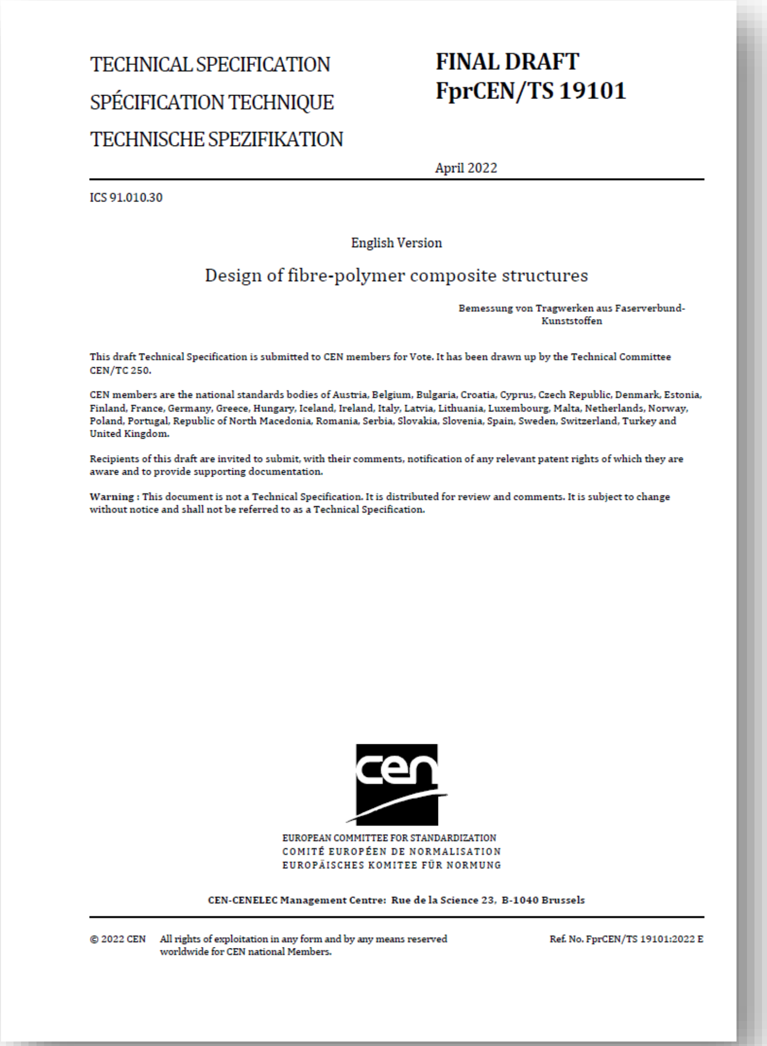
The **conversion factor for temperature**, η_{ct}, is determined according to the following general equation, considering a **reference material temperature** of 20 °C:

$$\eta_{ct} = \min\left\{1{,}0 - \alpha \cdot \frac{T_s - 20\ ^{\circ}\mathrm{C}}{T_g - 20\ ^{\circ}\mathrm{C}};\ 1{,}0\right\}$$

α	**Composite materials, sandwich core materials and adhesives**
0,25	For **fibre-dominated properties** of **composite materials** with glass, carbon or basalt fibres and thermoset polymer matrix of either unsaturated polyester, vinylester or epoxy
0,80	For **matrix-dominated properties** of **composite materials** with glass, carbon or basalt fibres and thermoset polymer matrix of either unsaturated polyester, vinylester or epoxy
0,46	For **polymeric foam core materials**, namely polyurethane (PUR), polyethylene terephthalate (PET) and polyvinyl chloride (PVC) foams (densities from 40 to 300 kg/m^3)
0,85	For **epoxy adhesives**

How durability is addressed in the Codes?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The **conversion factor for moisture**, η_{cm}, for for **unprotected composite materials** (glass, carbon or basalt fibres; thermoset polymer matrix of unsaturated polyester, vinylester or epoxy; fibre volume fraction of at least 35%) and **epoxy adhesives**:

Exposure classes	Influence of moisture	η_{cm}
I	**Indoor exposure** with service temperature	**1,0**
II	**Outdoors exposure** with service temperature, 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	**0,85**
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)	**0,60**

What is Viscoelasticity?

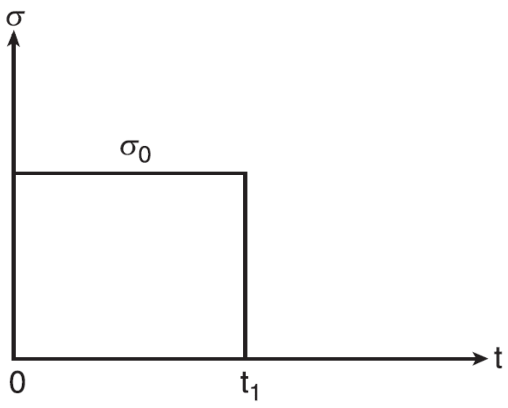
- **Viscoelasticity** is the property of materials that exhibit both **viscous** and **elastic** characteristics when undergoing deformation (during the time).

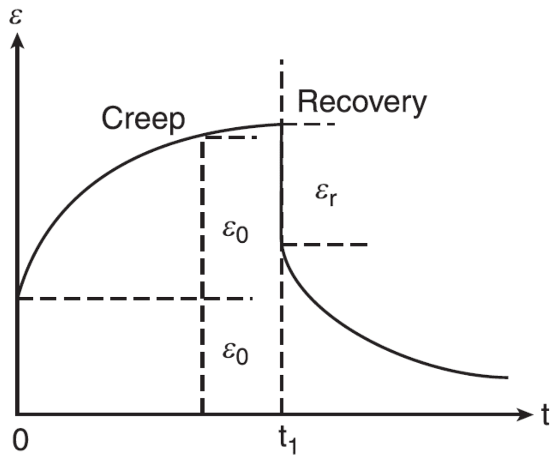
- A **viscous** material exhibits **time dependent behavior**: when a **constant stress is applied** it **deforms at a constant rate**. When the **load is removed**, the material has **‘forgotten’** its **original configuration**, remaining in the **deformed state**.

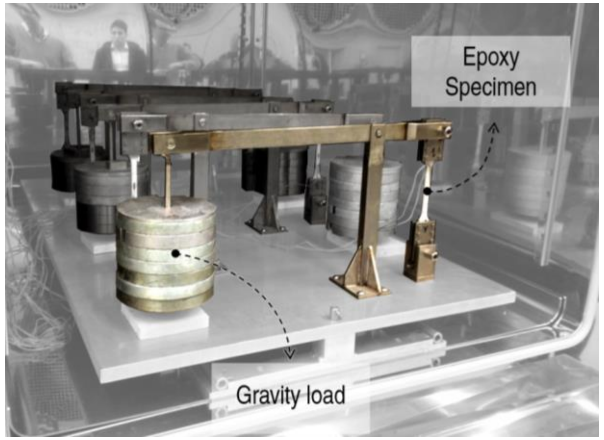
- An **elastic** material **deforms instantaneously** when **stressed** and ‘remembers’ its original configuration, **returning instantaneously to its original state** once the **stress** is **removed**.

What is Creep and Relaxation?

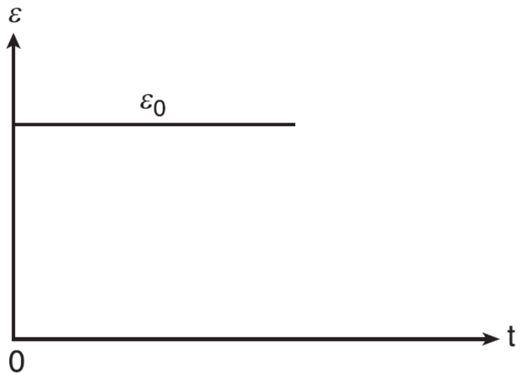
- **Creep** is a **slow** and **continuous deformation** of a material under **constant stress**.

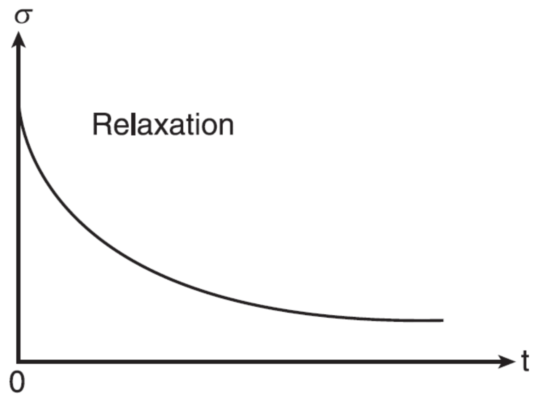


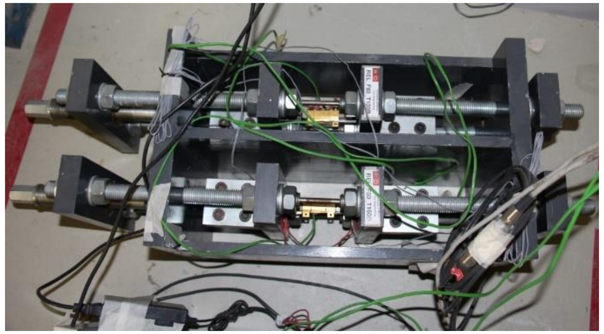




- **Relaxation** is a **gradual** and **continuous stress decrease** under **constant strain**.







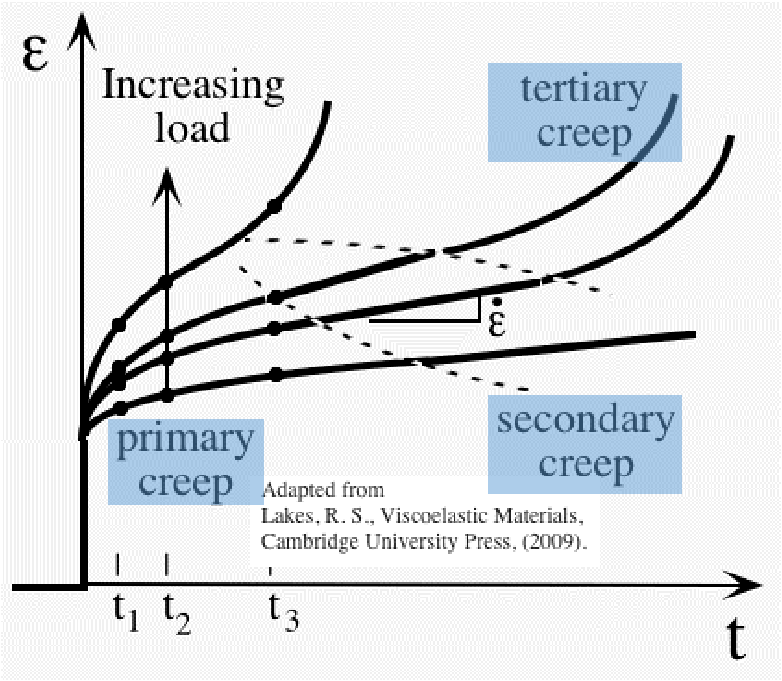
Creep stages

- Creep can be described in **three stages**:

  I. **Primary creep:** the material undergoes deformation at a decreasing rate;

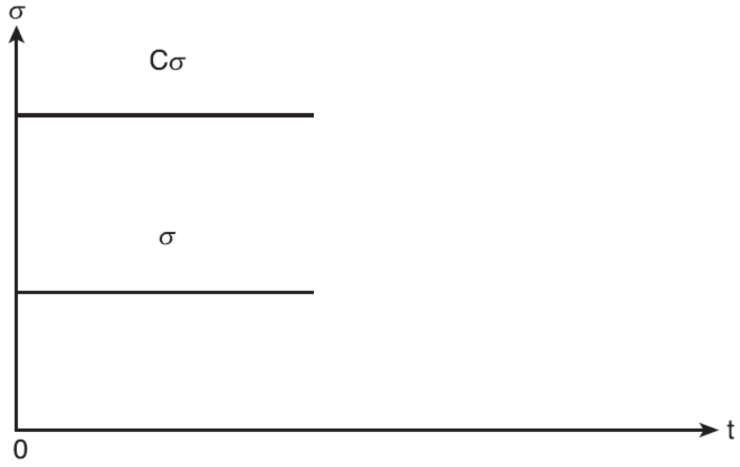
  II. **Secondary creep:** the material progresses at a nearly constant rate;

  III. **Tertiary creep:** it occurs at an increasing rate and ends with fracture of the material.



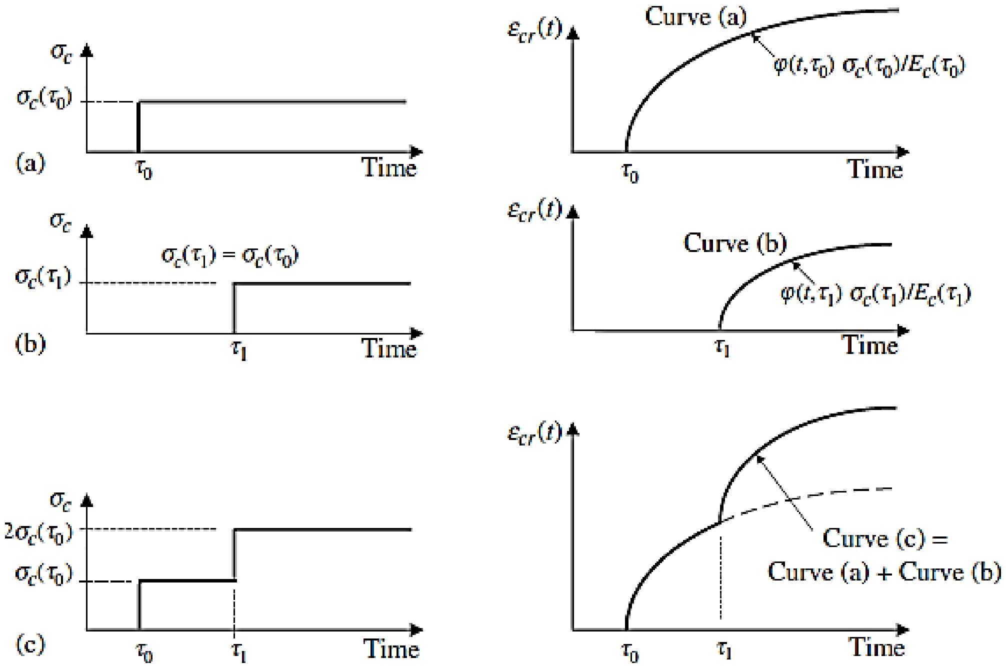
Linearity in creep: Homogeneity + Superposition Principle

Homogeneity



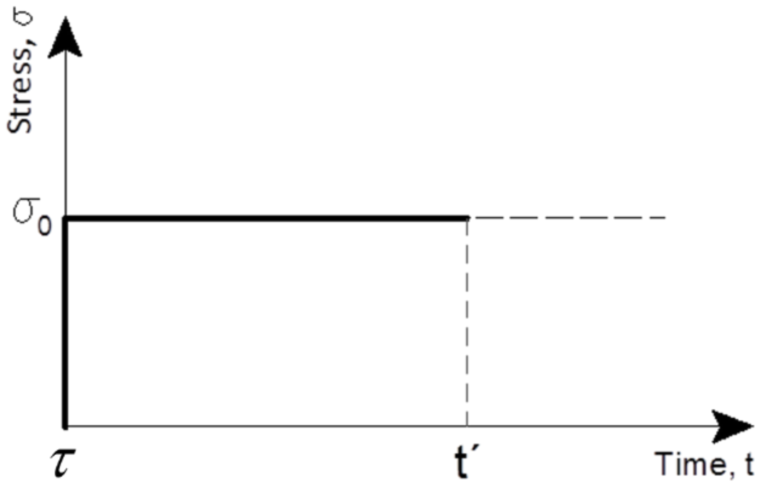
$$\varepsilon_x\left\{c\sigma_x\right\} = c\varepsilon_x\left\{\sigma_x\right\}$$
$$c = const$$

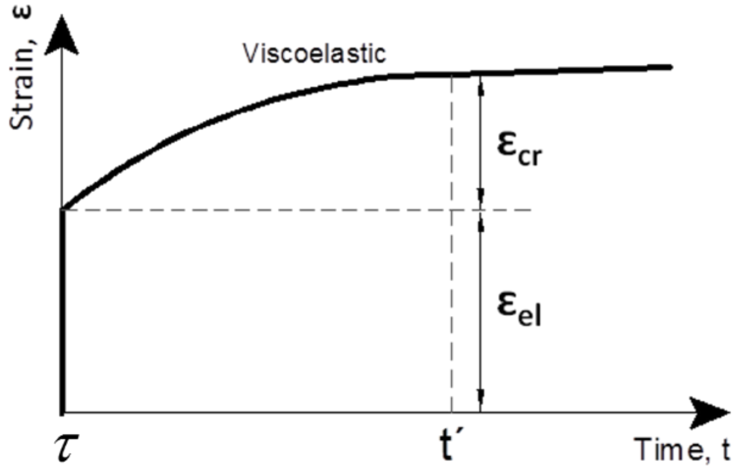
Superposition Principle



$$\varepsilon_x(\sigma_x^1 + \sigma_x^2) = \varepsilon_x\left\{\sigma_x^1\right\} + \varepsilon_x\left\{\sigma_x^2\right\}$$

Creep: Creep compliance (J) and Creep coefficient (φ)





$$\sigma(t) = \varepsilon_{\sigma} \cdot E(t) \qquad \varepsilon(t) = \sigma_0 \cdot J(t)$$

$$\varphi(t,\tau) = \frac{\varepsilon_{cr}(t,\tau)}{\varepsilon_e(\tau)}$$

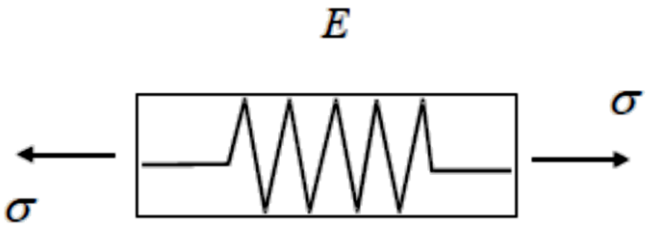
$$\varepsilon(t) = \varepsilon_e(t) + \varepsilon_{cr}(t)$$

$$J(t,\tau) = \frac{1}{E_c(\tau)} \cdot \left[1 + \varphi(t,\tau)\right]$$

$$\varepsilon_e(t) + \varepsilon_{cr}(t) = J(t,\tau) \cdot \sigma_0 = \frac{\sigma_0}{E_c(\tau)} \cdot \left[1 + \varphi(t,\tau)\right]$$

Rheological Models: Basic components

Linear elastic spring



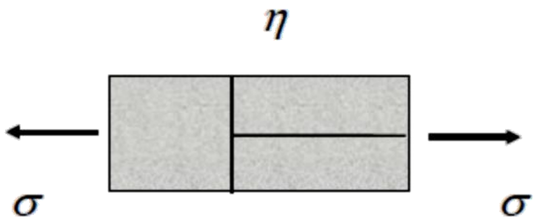
Hooke Model – typical of solids

$$\varepsilon = \frac{1}{E} \cdot \sigma$$

ε – deformation, strain

E – elastic modulus

Linear viscous dash-pot



Newton Model – typical of flows

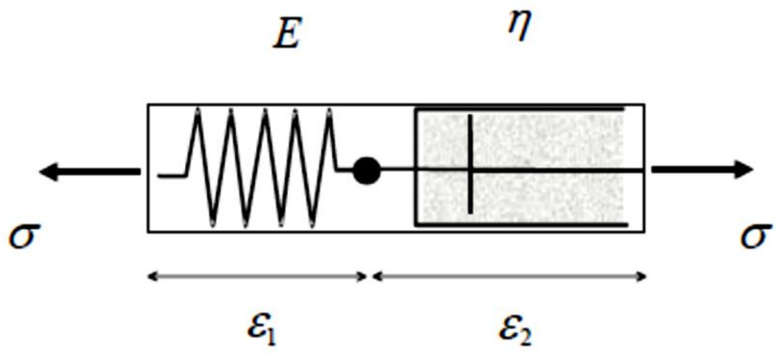
$$\dot{\varepsilon} = \frac{1}{\eta} \cdot \sigma$$

σ – stress applied

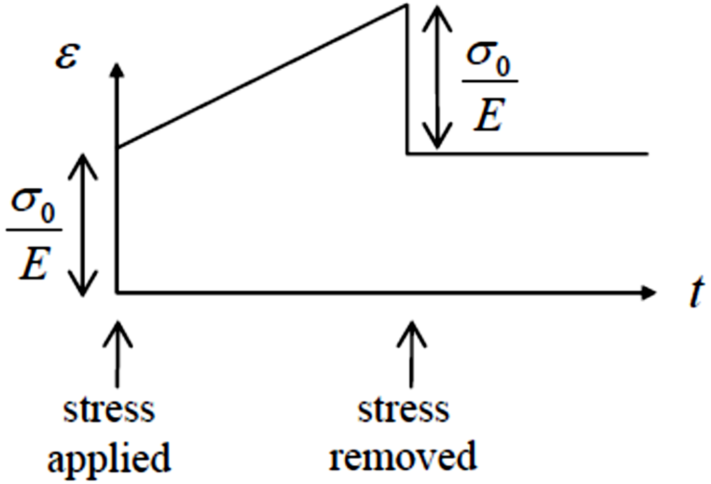
η – viscosity

Rheological Models (1/2)

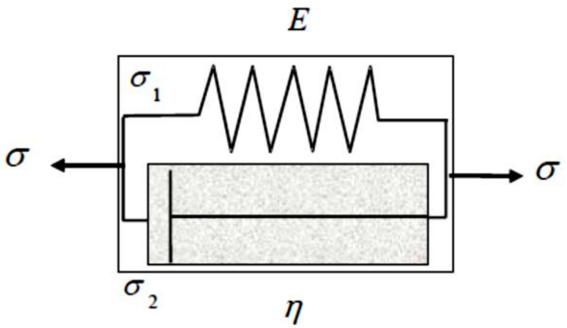
Maxwell fluid model



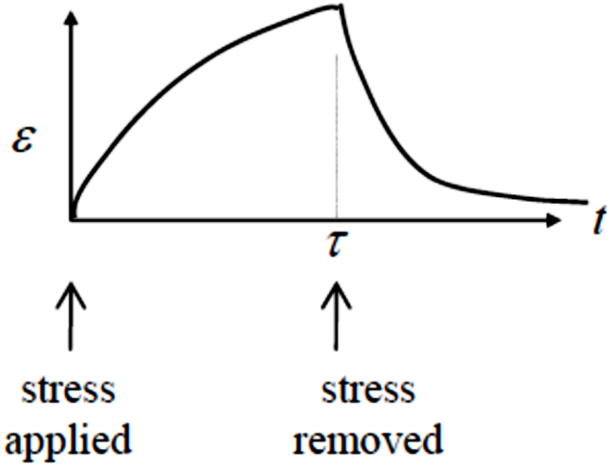
$$\dot{\varepsilon}(t)=\frac{\dot{\sigma}(t)}{E}+\frac{\sigma(t)}{\eta}$$



Kelvin (Voigt) solid model

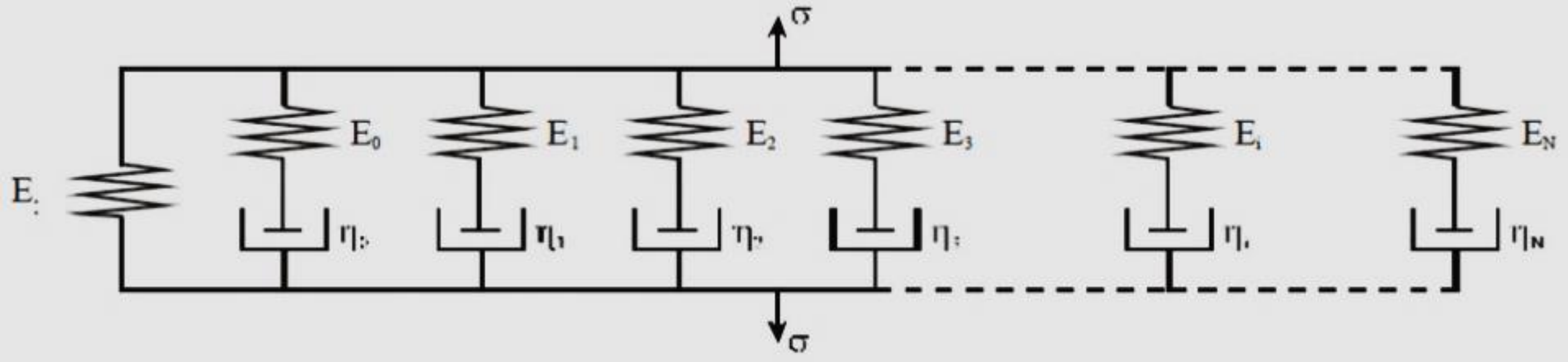


$$\dot{\varepsilon}(t)=\frac{\sigma(t)}{\eta}+\frac{E\cdot\varepsilon(t)}{\eta}$$

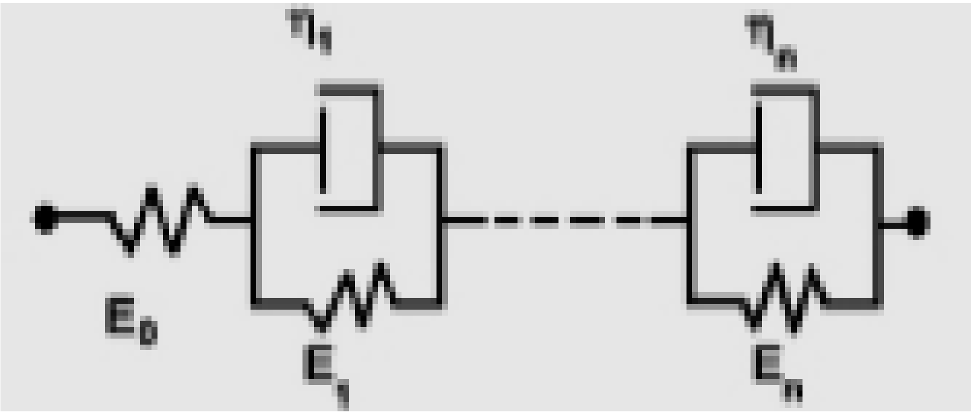


Rheological Models (2/2)

Maxwell generalized model



Kelvin generalized model



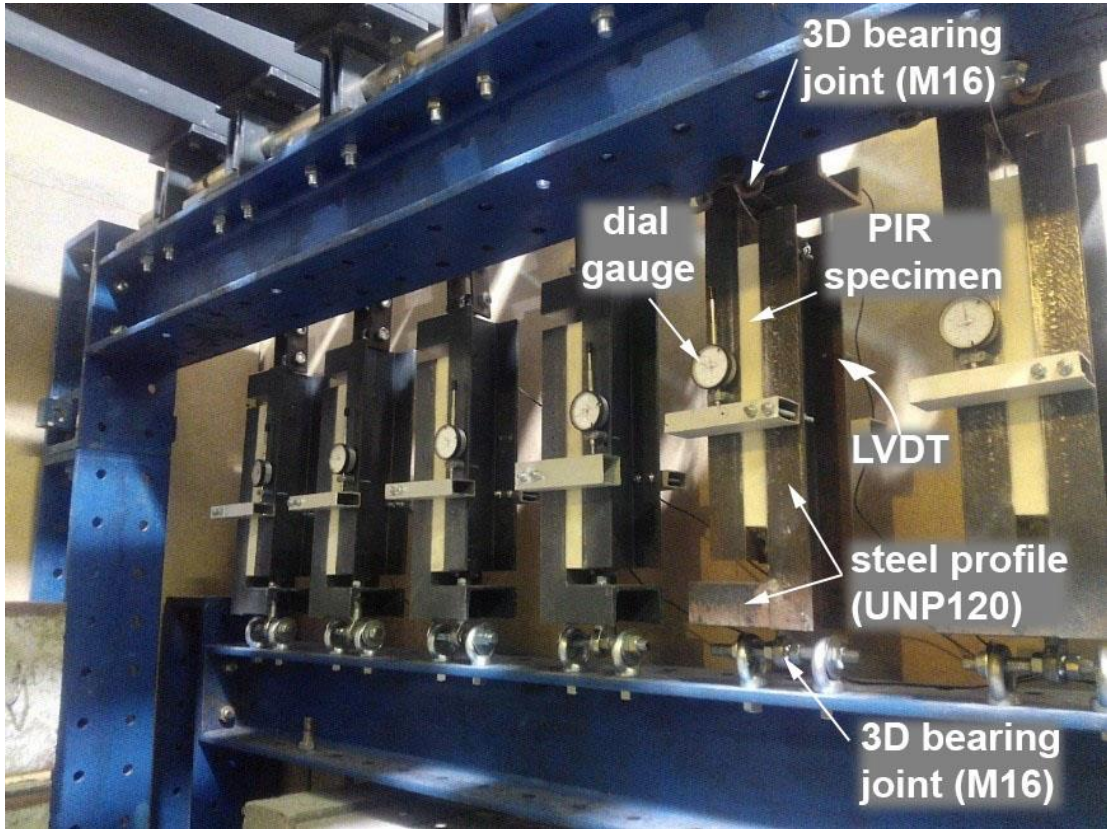
Creep Model for Composite Materials: Findley's power law

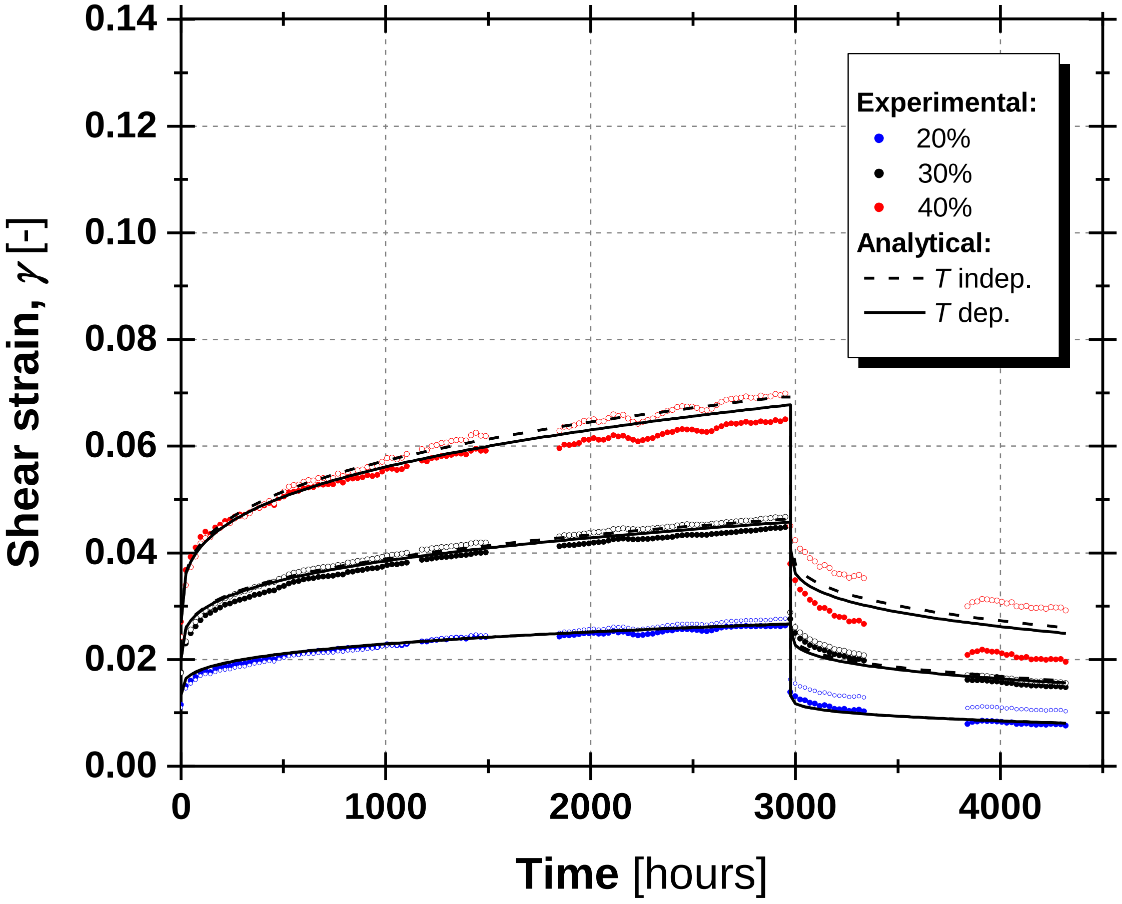
$$\delta(t) = \delta_e + m \times \left(\frac{t}{t_o}\right)^n$$

- $\delta(t)$: Displacement/strain during the time
- δ_e: Elastic displacement/ strain
- m: Creep amplitude coefficient (applied stress dependent)
- t: time
- t_o: time unit
- n: Coefficient (material dependent for a given hygrothermal condition)

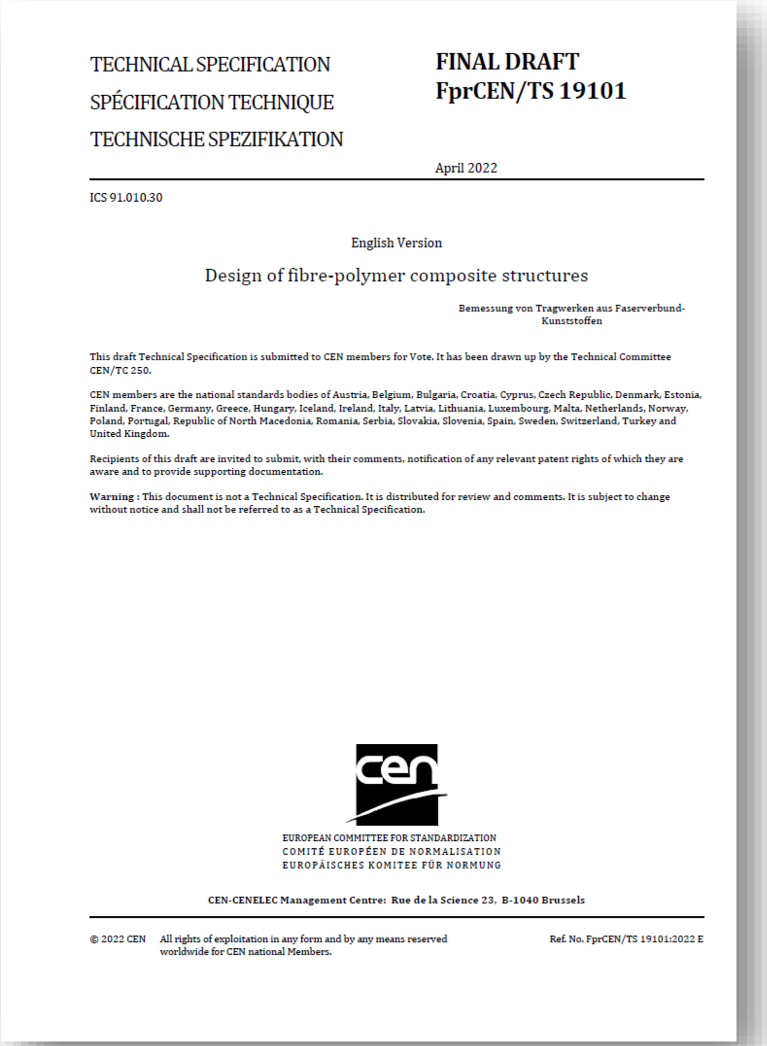
Creep Model for Composite Materials: Findley's power law

Creep of a PUR foam (40 kg/m³)





How creep is taken into accounted in the Codes?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SPÉCIFICATION TECHNIQUE
TECHNISCHE SPEZIFIKATION

FINAL DRAFT
FprCEN/TS 19101

April 2022

ICS 91.010.30

English Version

Design of fibre-polymer composite structures

Bemessung von Tragwerken aus Faserverbund-Kunststoffen

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COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

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

Ref. No. FprCEN/TS 19101:2022 E

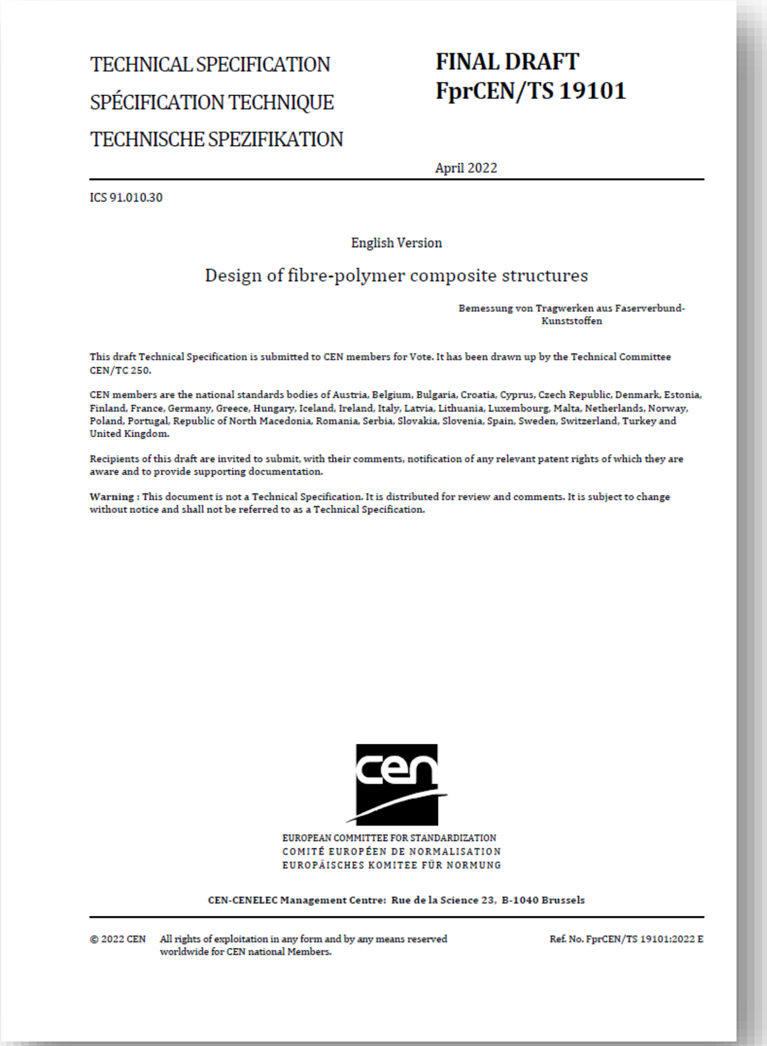
❑ Serviceability verification (Linear creep)

Creep effects on the **deformations** of composite structures should be taken into account by **reducing the initial mean values of the relevant elastic moduli of materials**, through a **creep coefficient**:

$$X_m(t) = \frac{X_m(0)}{1 + \phi(t)}$$

t	= time
$X_m(t)$	= **mean value of elastic** or **shear modulus** at time to take into account creep effects
$X_m(0)$	= **initial mean value of elastic** or **shear modulus** (at time '0')
$\phi_m(t)$	= **creep coefficient** at time t

How creep is taken into accounted in the Codes?



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❑ Serviceability verification (Linear creep)

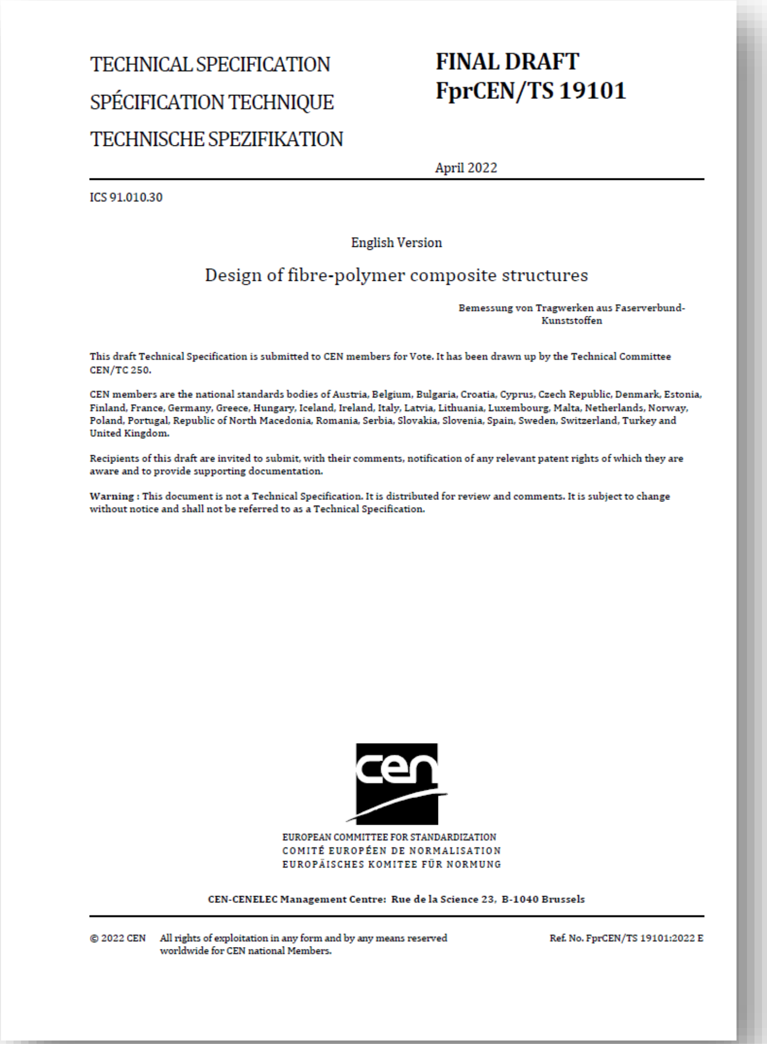
Table A.1 — Values for the creep coefficient, $\phi(t)$, for different elastic moduli of pultruded composite profiles (glass, carbon or basalt fibres; fibre volume fraction of at least 35%; temperature up to 25 °C; relative humidity up to 65%)

Property	Period of time (years)										
	1	5	10	15	20	25	30	40	50	75	100
E_x^{full}	0,25	0,38	0,46	0,51	0,55	0,58	0,61	0,66	0,70	0,78	0,84
G_{xy}^{full}	0,57	0,98	1,23	1,40	1,54	1,66	1,76	1,94	2,09	2,39	2,62
$E_{x,t}$	0,20	0,22	0,24	0,24	0,25	0,25	0,25	0,26	0,26	0,27	0,28
$E_{x,c}$	0,20	0,23	0,27	0,30	0,32	0,34	0,36	0,38	0,41	0,45	0,48

×3.7

×2.8

How creep is taken into accounted in the Codes?



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❑ Serviceability verification (Linear creep)

Table A.2 — Values for the creep coefficient, $\phi(t)$, for different elastic moduli of composite laminates/plies (glass, carbon or basalt fibres; fibre volume fraction of at least 35%; temperature up to 25 °C; relative humidity up to 65%)

Type of fibres	Property	Period of time (years)										
		1	5	10	15	20	25	30	40	50	75	100
UD	$E_{x,t}$	0,10	0,11	0,12	0,13	0,13	0,13	0,13	0,14	0,14	0,14	0,15
	$E_{x,c}$	0,15	0,23	0,27	0,30	0,32	0,34	0,36	0,38	0,41	0,45	0,48
	G_{xy}	1,13	1,55	1,78	1,94	2,06	2,16	2,25	2,40	2,52	2,78	2,94
Woven (0/90°)	$E_{x,t}$, $E_{x,c}$	0,44	0,53	0,58	0,60	0,62	0,64	0,65	0,67	0,68	0,71	0,73
CSM	$E_{x,t}$, $E_{x,c}$	1,48	1,91	2,12	2,25	2,34	2,42	2,48	2,58	2,67	2,82	2,93

How creep is taken into accounted in the Codes?

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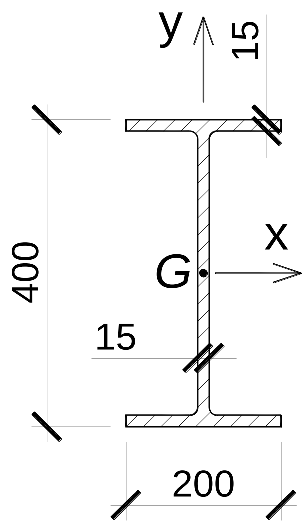
❑ Serviceability verification (Linear creep)

Table A.3 — Values for the creep coefficient, $\phi(t)$, for the out-of-plane shear modulus, G_{xz}, of different core materials (temperature up to 22 °C for polymeric foams and up to 25 °C for balsa wood; relative humidity up to 65%)

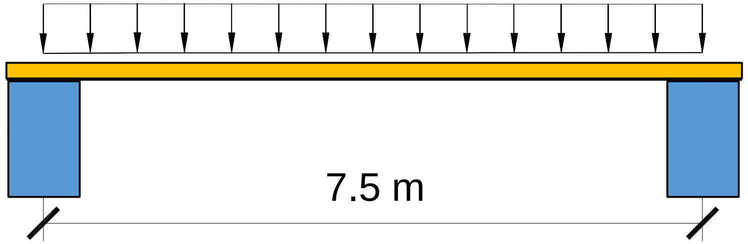
Material	Property	Period of time (years)										
		1	**5**	**10**	**15**	**20**	**25**	**30**	**40**	**50**	**75**	**100**
PUR foam (up to 100 kg/m³)	G_{xz}	3,34	4,19	4,60	4,86	5,05	5,20	5,33	5,54	5,70	6,01	6,24
PET foam (up to 100 kg/m³)	G_{xz}	0,03	0,21	0,31	0,38	0,44	0,49	0,53	0,60	0,65	0,77	0,86
End-grain balsa (up to 100 kg/m³)	G_{xz}	0,70	1,59	2,11	2,47	2,74	2,97	3,16	3,49	3,75	4,28	4,69

How creep is taken into accounted in the Codes?



Pultruded GFRP I400 profile:

- A_{web} = 60 cm^2
- I_{xG} = 28576.625 cm^4
- E_L = 30 GPa
- G_{LT} = 3.5 GPa



$$\delta(t) = \frac{5}{384} \cdot \frac{p \cdot l^4}{E(t) \cdot I} + \frac{1}{8} \cdot \frac{p \cdot l^2}{G(t) \cdot A'}$$

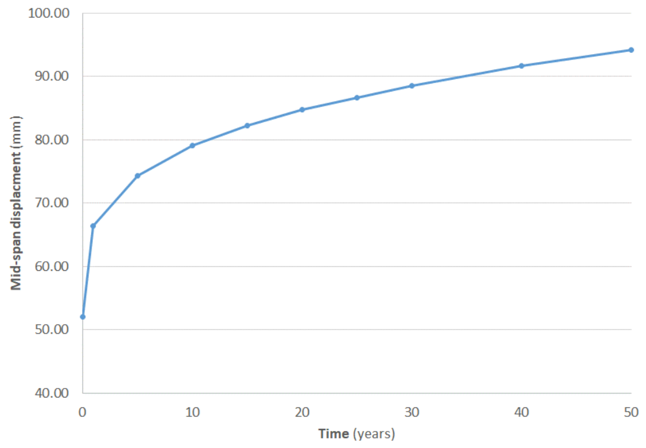
$$E(t) = \frac{E_L}{1+\phi_E(t)}$$

$$G(t) = \frac{G_{LT}}{1+\phi_G(t)}$$

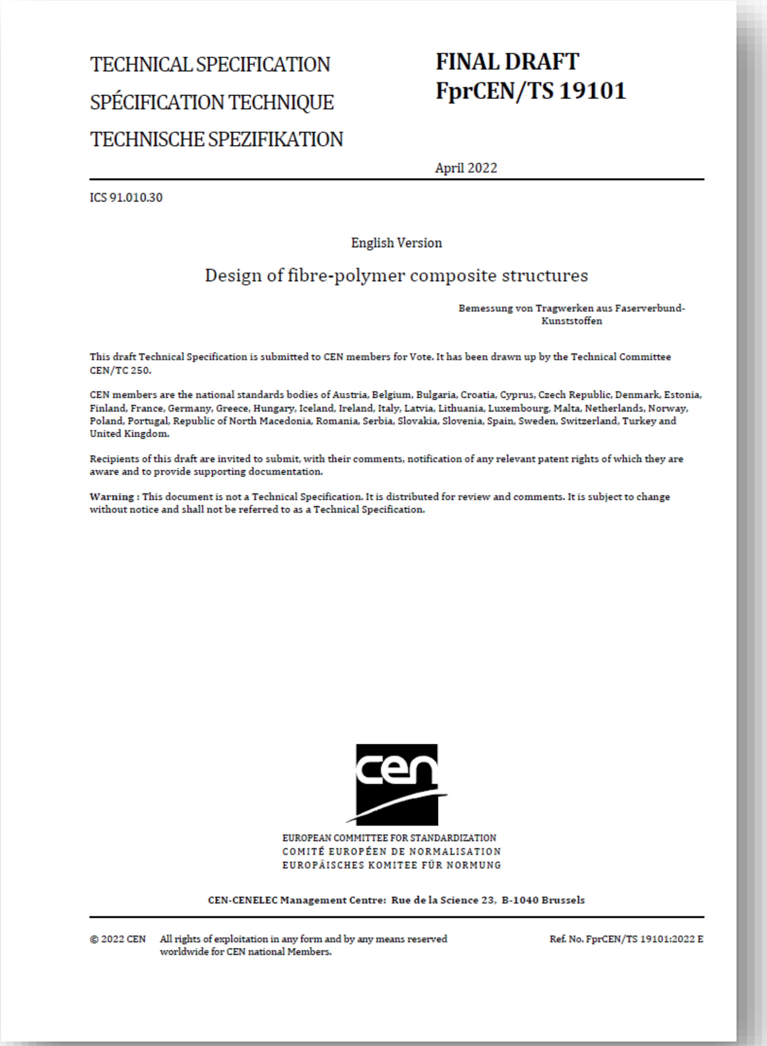
Mid-span displacement (mm)

Time (years)	Timoshenko beam				
	Flexural	Shear	Total	Flexural	Shear
0	48.06	4.02	52.07	92.3%	7.7%
1	60.07	6.31	66.38	90.5%	9.5%
5	66.32	7.96	74.27	89.3%	10.7%
10	70.16	8.96	79.12	88.7%	11.3%
25	75.93	10.69	86.62	87.7%	12.3%
50	81.70	12.42	94.11	86.8%	13.2%

(Based on Table A1. of FprCEN/TS 19101:2022)



How creep is taken into accounted in the Codes?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❑ Ultimate verification (Creep rupture)

Creep rupture of composite members and components **can be prevented by limiting sustained stresses** (example for the case of tensile stresses):

$$\sigma_{t,creep,Ed} \leq \sigma_{t,creep,Rd} = \frac{\eta_c}{\gamma_{M,creep}} \cdot k_{t,creep} \cdot f_{c,t,k}$$

η_c = conversion factor

$\gamma_{M,creep}$ = partial factor for creep rupture

$k_{t,creep}$ = strength reduction factor for tensile creep rupture for continuous unidirectional fibres

$f_{i,t,k}$ = characteristic value of the tensile strength of the composite laminate in the fibre (*i*) direction

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

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