Advanced Composites in Engineering Structures

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Lecture VII: Durability and long-term behaviour of composites

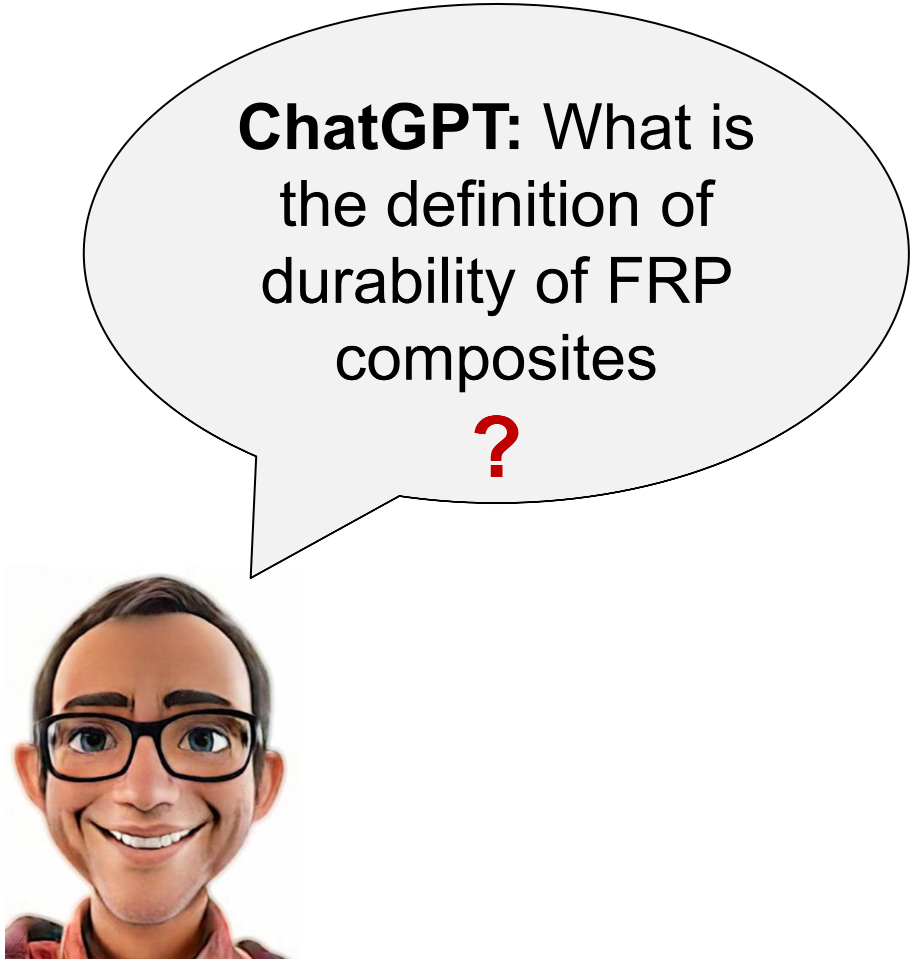
EPFL

GR MeC
Composite Mechanics Group

Section 1

Introductory aspects

Introductory aspects



The durability of **FRP (Fiber Reinforced Polymer) composites** refers to their **ability to maintain mechanical and structural integrity over an extended period under various environmental conditions, loads, and external factors.**

Durability in FRP composites is typically assessed by how well they resist degradation caused by factors like:

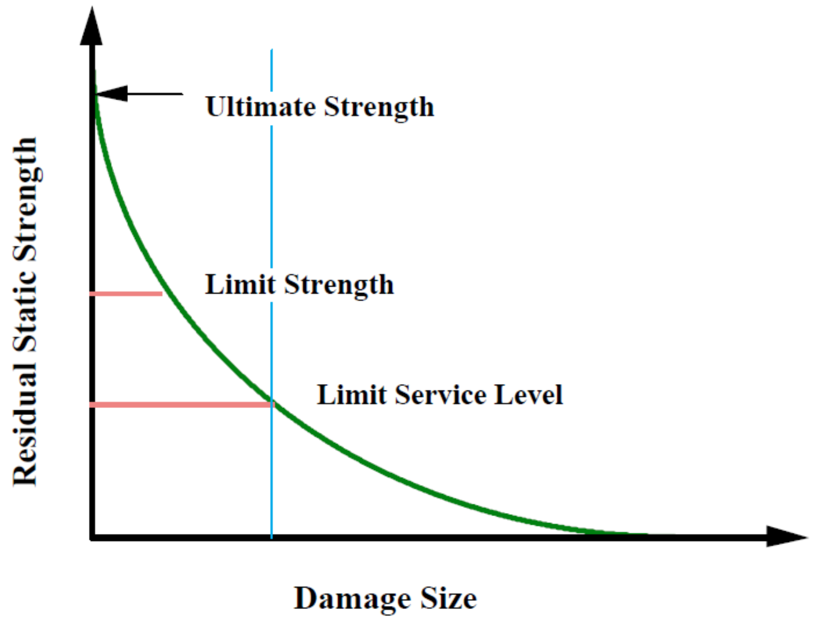
- **Environmental exposure**
- **Mechanical stresses**
- **Corrosion resistance**
- **Creep and fatigue**

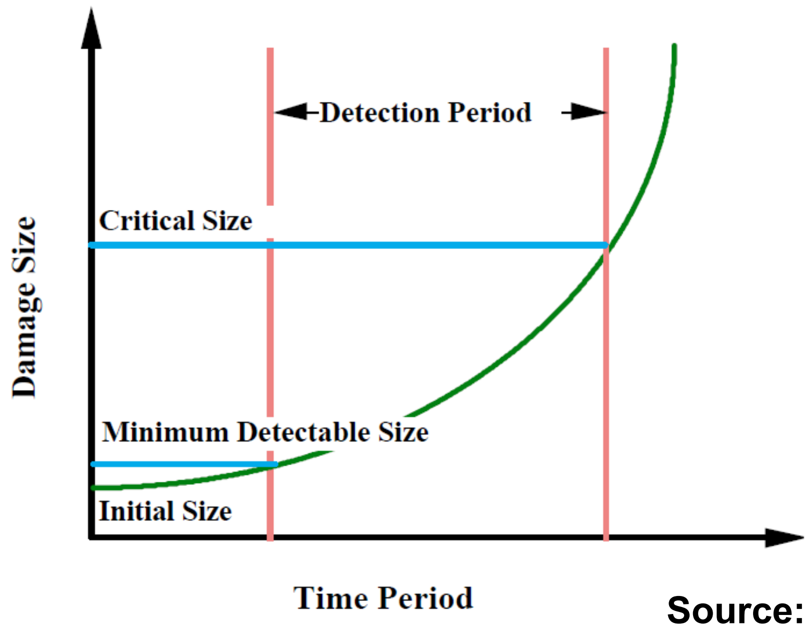
The durability of **FRP composites plays a critical role in their application**, especially in industries like **aerospace, civil engineering, automotive, and marine**, where long-term performance and minimal maintenance are required.

Introductory aspects

❑ What is durability?

- "***Durability*** *of a material, component or structure 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**.*"





Source: ISBN 0-7844-0578-6

Introductory aspects

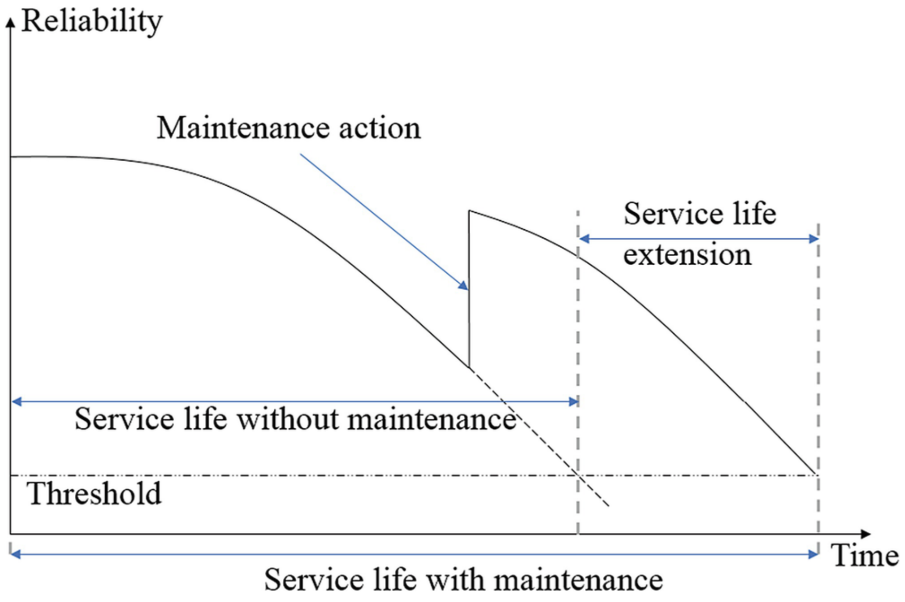
❑ Design working life (Eurocode "0")

- *"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 <u>due regard to its environment and the anticipated level of maintenance</u>."*

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

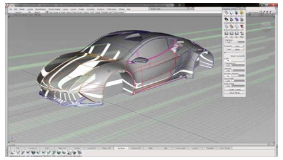
(1) Structures or parts of structures that can be dismantled with a view to being re-used should not be considered as temporary.



Introductory aspects

❑ Durability - Complexity of phenomena

- Although **composite materials have been successfully used** in the construction, automotive, marine, wind energy, and aerospace sectors, **there are critical differences among each application** 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**.



Introductory aspects

❑ Degradation factors

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

Introductory aspects

❑ Degradation mechanisms

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.

Examples of **degradation mechanisms**:

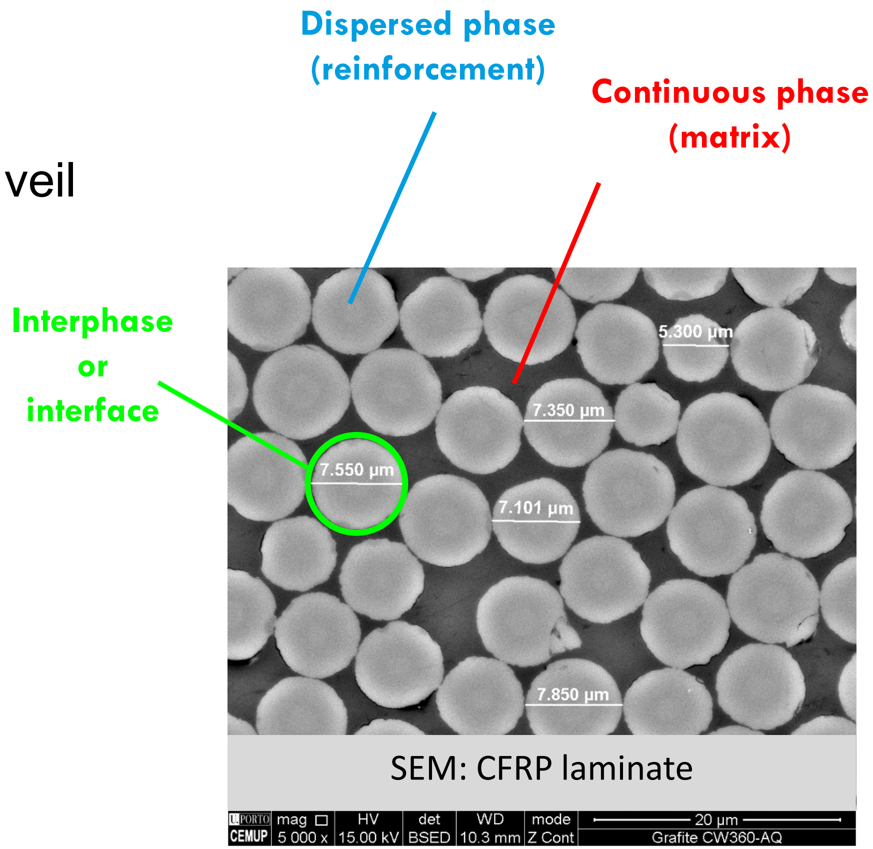
- **Physical:** Plasticization, Relaxation
- **Mechanical:** Debonding
- **Chemical:** Hydrolysis, Leaching

Introductory aspects

❑ 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)

Introductory aspects

❑ Durability assessment of the specific environmental degradation factors

Identification: set the relevant parameters of the environmental degradation factor

Planning of aging tests that can include accelerated aging and/or natural aging

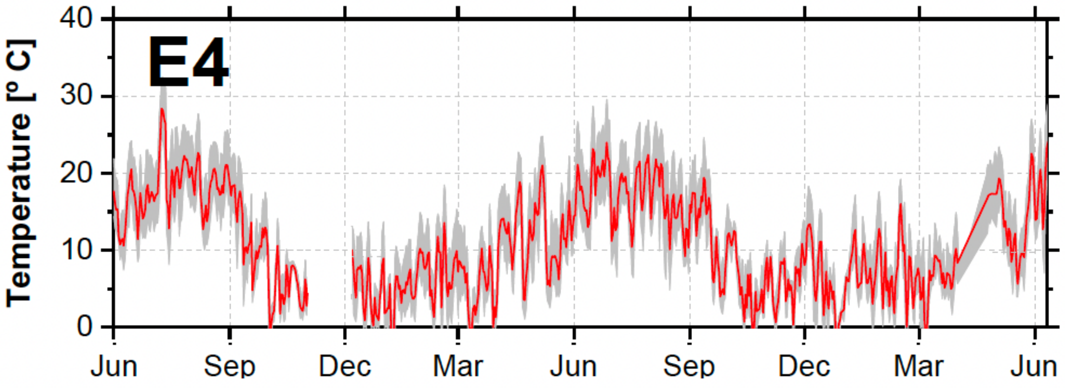
Assessment of the durability performance, including degradation mechanisms in the process of aging in the aging tests

Lifetime prediction (modelling) and eventual **correlations** between accelerated aging and natural aging

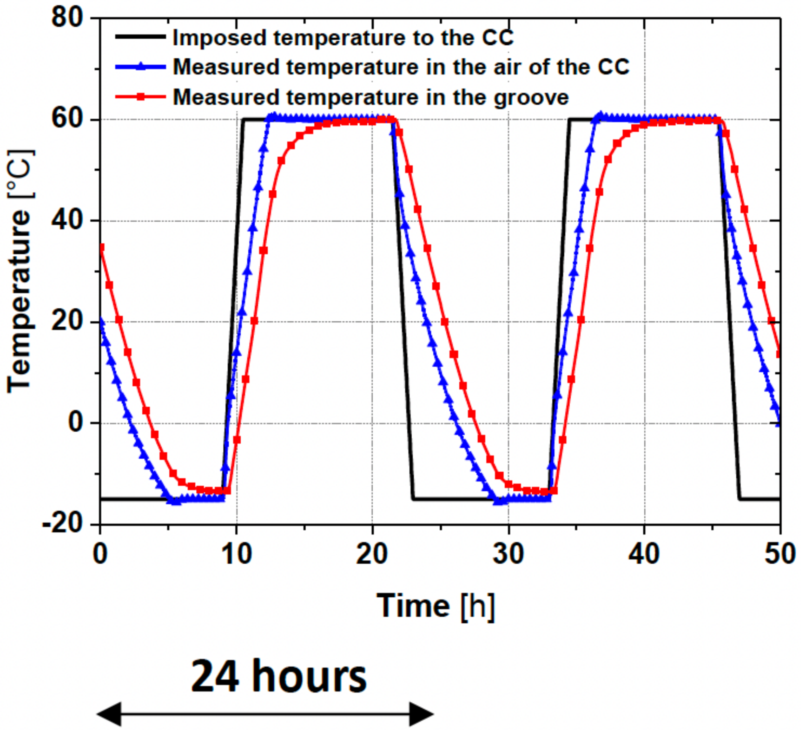
Introductory aspects

❑ Artificial accelerated aging *versus* natural aging

Natural Aging



Artificial Aging



Section 2

Durability

Section 2.1

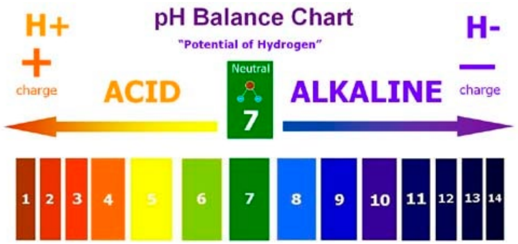
Environmental degradation factors

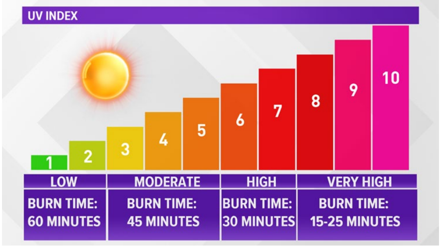
Durability

❑ Environmental degradation factors

The main environmental degradation factors affecting composites, acting in isolation or in combination are:

- **Temperature**
- **Moisture**
- **Chemicals**
- **Ultraviolet (UV) radiation**





Durability - Temperature

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

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

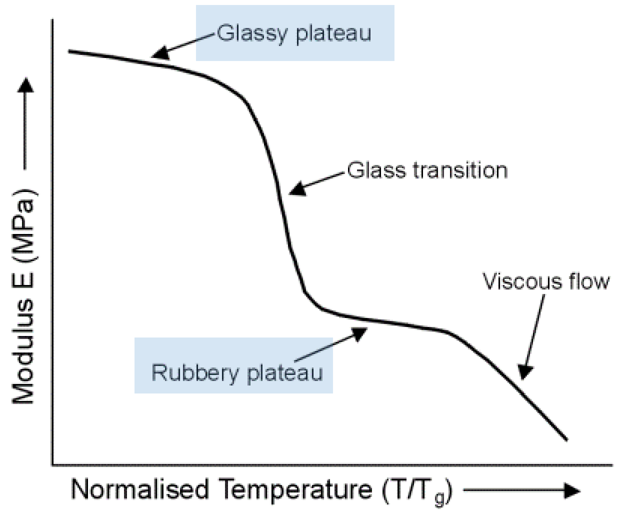
- Additionally, **test methods** adopted in the studies **vary significantly**, with respect to
  - the constituent materials (fibre and resin),
  - manufacturing processes,
  - type and exposure conditions, and,
  - characterisation techniques.

Durability - Temperature

- 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.

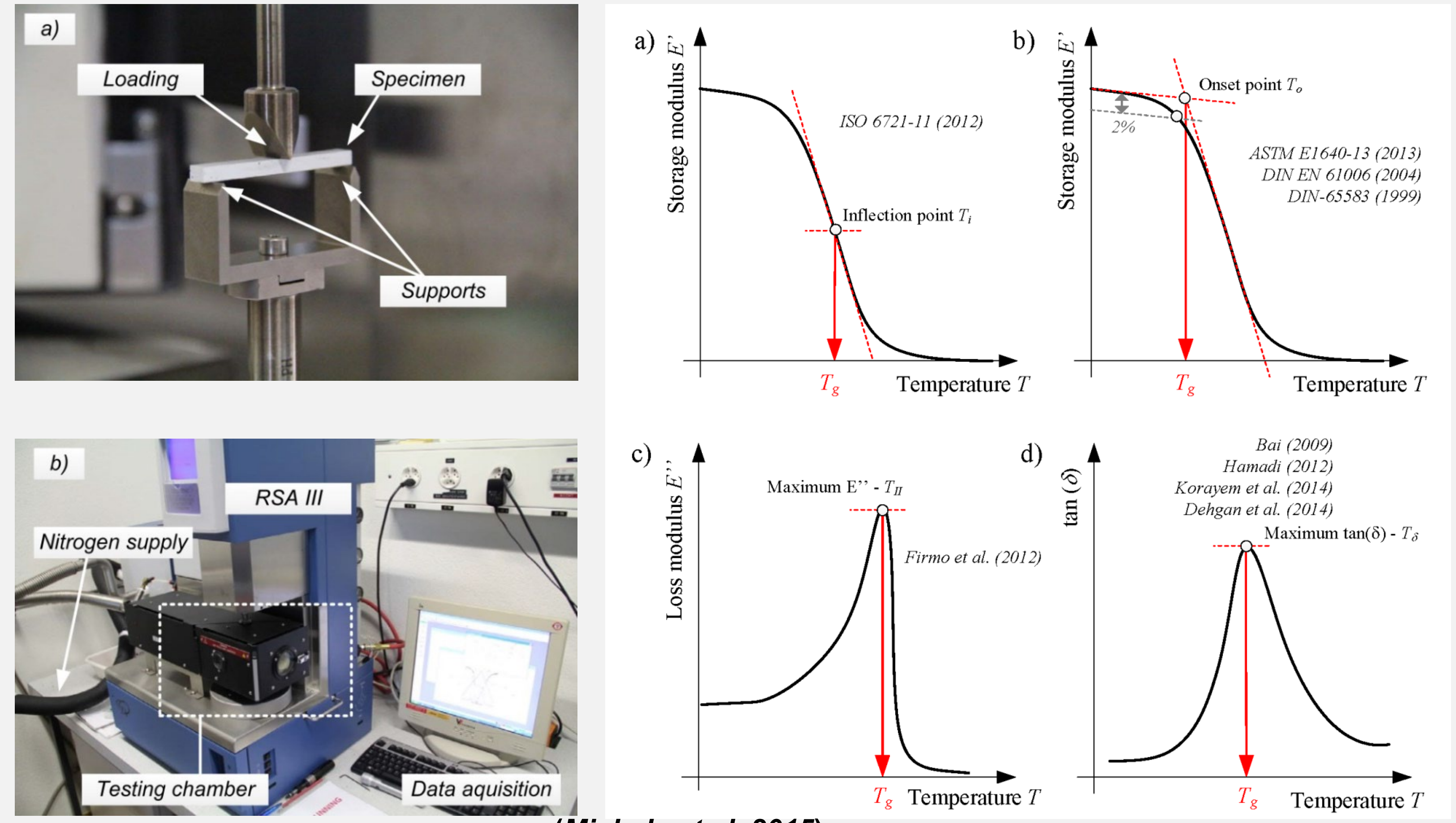
  - By **cooling the polymeric matrix** from temperatures **above** T_g to temperatures **below** T_g result into **a full recovery of its mechanical properties**.



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)

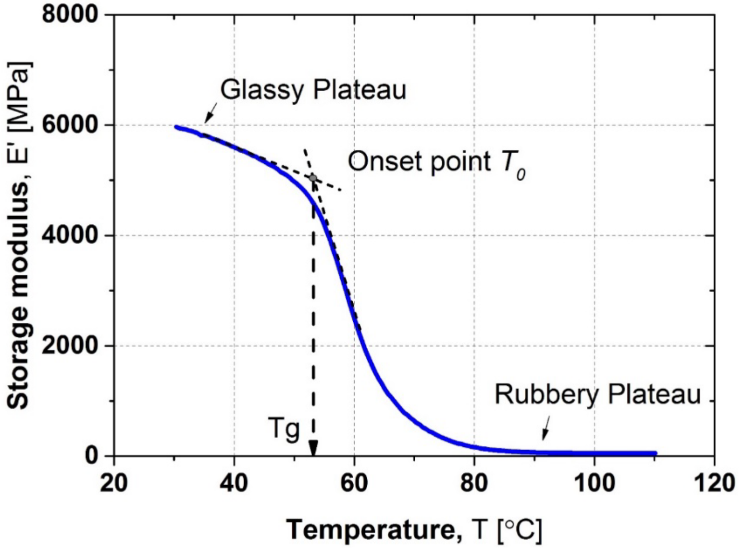
Durability - Temperature

- ❑ What is **glass transition temperature**?



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

Example of a DMA test of an epoxy adhesive



Durability - Temperature

❑ Effects on the composite materials

- **Exposure to elevated temperatures** led to **reduction on the strength and stiffness** when approaching T_g of the polymer matrix.
- **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 composite performance, namely by reducing its mechanical properties due to incompatible thermal expansion.

Durability - Temperature

❑ Low temperatures (LT) and cryogenic temperatures (CT)

Description	[K]	[°C]	Category
Room temperature			
Design temperature for Arctic conditions			
Design temperature for aircraft components			
Solid carbon dioxide (dry ice)			
Design temperature for cubesats			
Lowest temperature measured on Earth			
Liquid methane (LCH4) or natural gas (LNG)			
Lowest temperature in low Earth orbit (LEO)			
Liquid oxygen (LOX)			
Liquid nitrogen (LN_2)			
Liquid hydrogen (LH_2)			
Liquid helium (LHe)			
Temperature in empty space			
Absolute zero			

Source: Sápi, Z & Butler, R 2020, 'Properties of cryogenic and low temperature composite materials – A review', *Cryogenics*, vol. 111, 103190. https://doi.org/10.1016/j.cryogenics.2020.103190

Durability - Temperature

❑ Low temperatures (LT) and cryogenic temperatures (CT)

- The **tensile elastic modulus** and **strength** of the matrix tend to increase with decreasing temperature.
- Similarly to tension, the **compressive** modulus and strength of the resin increase and the failure strain decrease with decreasing temperature.
- The **shear** behavior of composites is primarily controlled by the behavior of the matrix.
- Fracture **toughness** is defined as the damage tolerance of materials as their ability to resist crack propagation. Improved fracture toughness has been observed at cryogenic temperatures.
- The general trend according to literature, is decreasing composites **impact** performance with decreasing temperature.

Source: Sápi, Z & Butler, R 2020, 'Properties of cryogenic and low temperature composite materials – A review', *Cryogenics*, vol. 111, 103190.

Durability - Temperature

❑ Mitigation measures

To avoid undesired degradation of composites, the following aspects should be considered:

- Fibres should be completely and well covered by resin;
- Composites should not have cracks, either on the surface or in throughout thickness;
- Composites 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.

Durability - Moisture

- Typically, **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.

Durability - 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.

Durability - Moisture

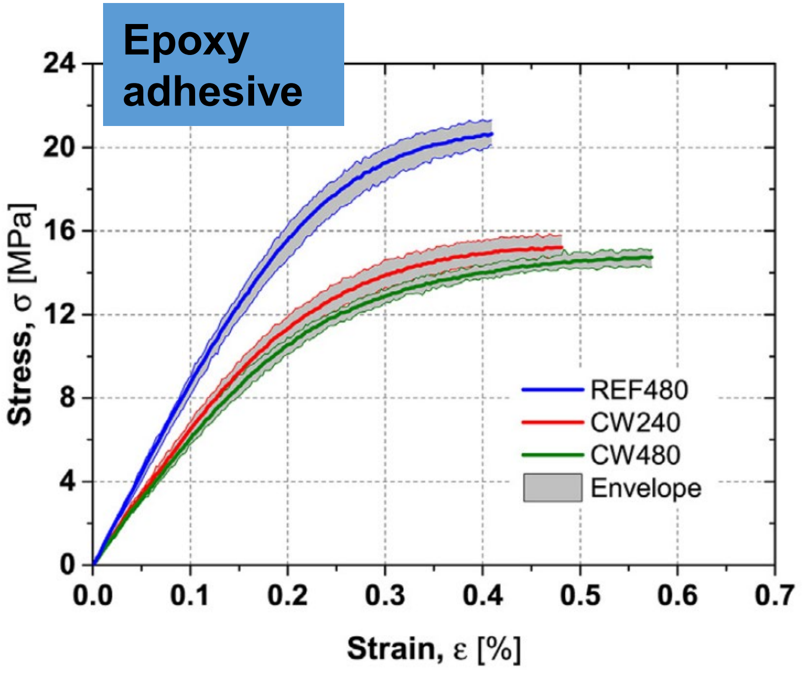
❑ Effects on FRP composite materials

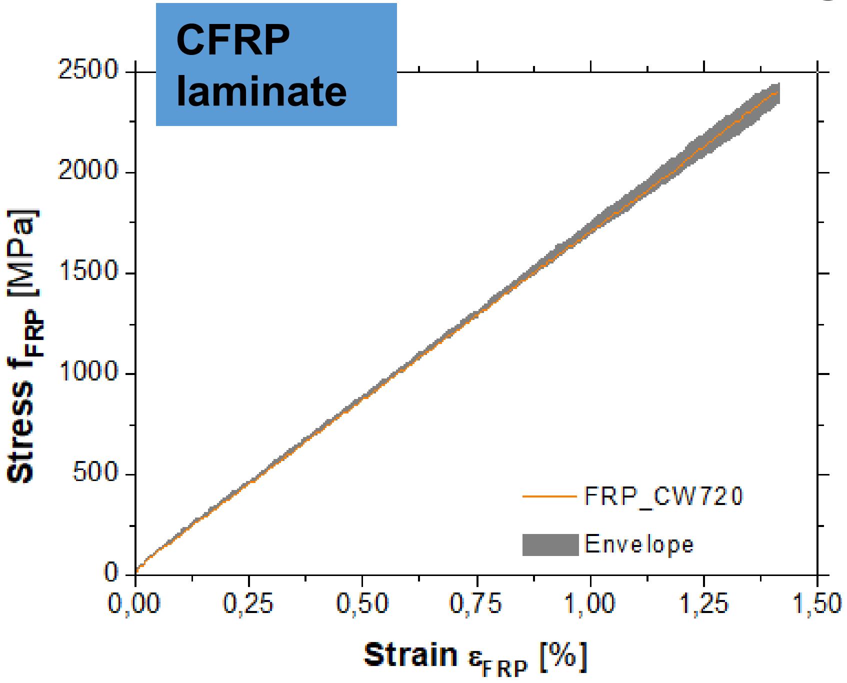
- Mechanical properties of composite materials **can be significantly affected by the presence of moisture**, as a result of the degradation of the matrix, the fibres and the interphase.
- **Degradation of composite materials** is generally **less sensitive** when compared to that experienced by the **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.

Durability - Moisture

❑ Example of epoxy adhesive vs. CFRP laminate

Up to ≈2 years of ageing!





E_{epoxy} ↘ -35% f_{epoxy} ↘ -28%

E_{CFRP} ↘ -1% f_{CFRP} ↘ -7%

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

Durability - Moisture

❑ Mitigation measures

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

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

2. 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**.

Durability - Chemicals

- **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).

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

Durability - Chemicals

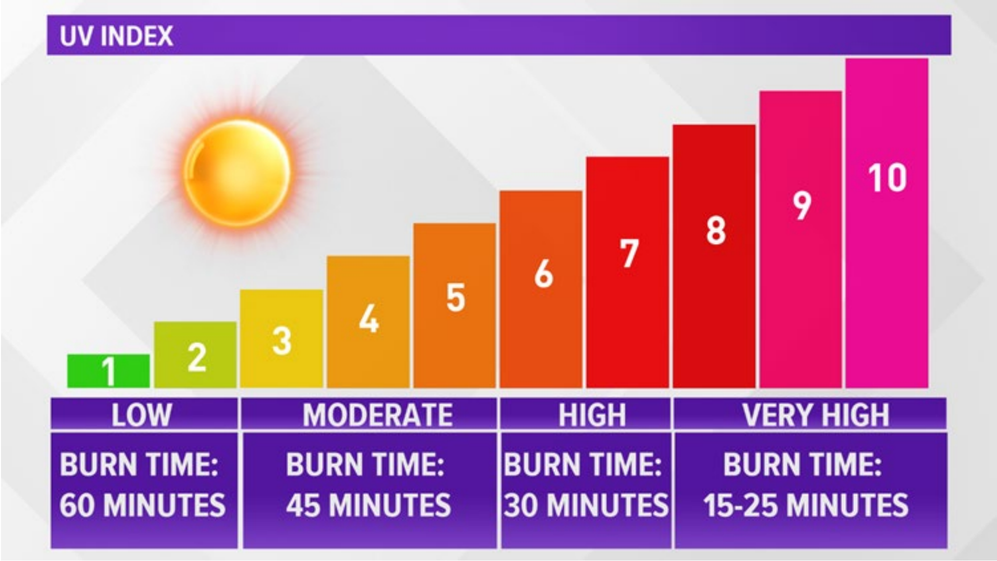
❑ Effects on composite materials

- In several sectors, **there are no standard test methodologies for assessing the chemical resistance** of composites.

- 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.

Durability - UV radiation

❑ Overall



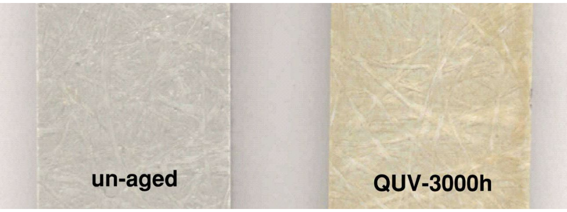
- **Outdoor composite structures** can be exposed to the **ultraviolet (UV) radiation** from the sun.
- **UV radiation affects mainly the polymer matrix** of composite materials. This may yield to detrimental in the overall mechanical properties of composite materials.
- Results show that the effects of exposure of **composite materials to UV radiation on are usually confined to the top few microns of the surface**, affecting especially their <u>aesthetical properties</u>: 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.

Durability - UV radiation

❑ 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

Durability - UV radiation

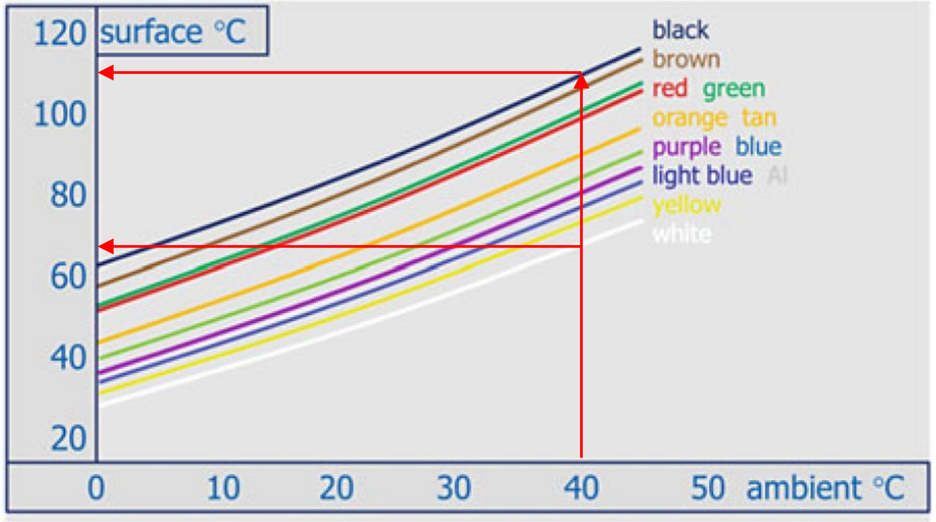
❑ Mitigation measures

The **strategies delay photodegradation** of 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

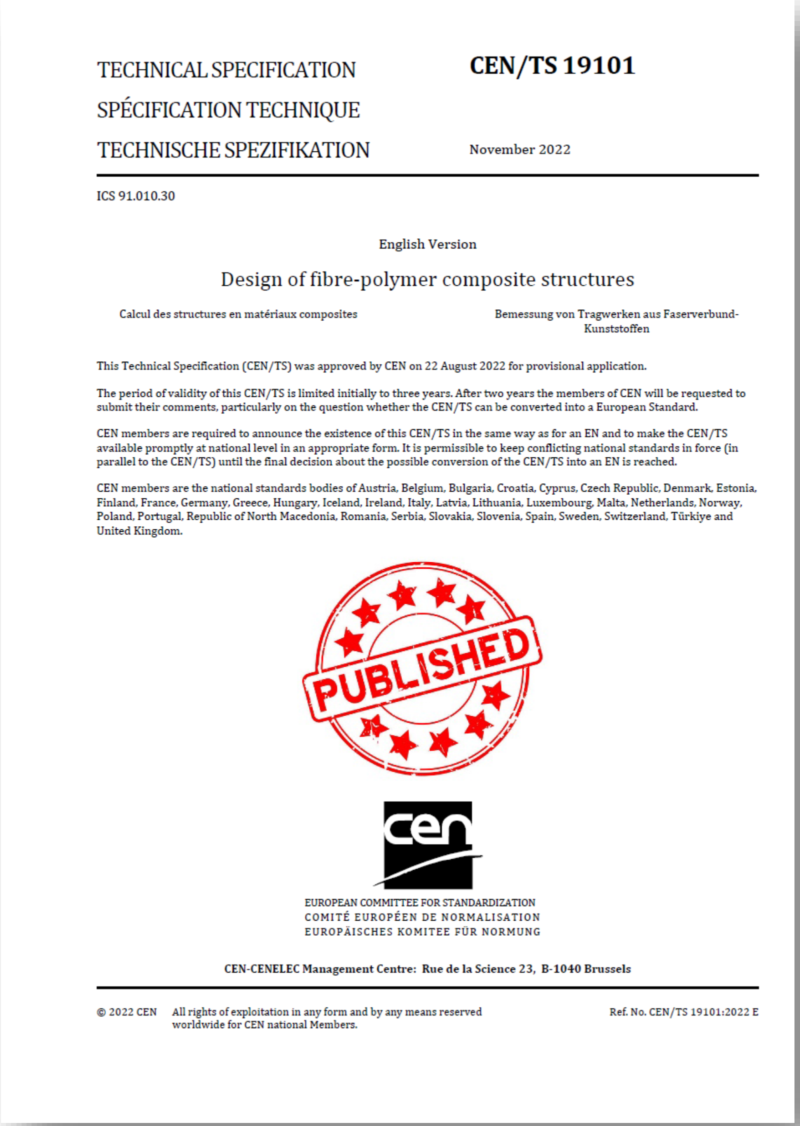


Source: P. Davies, Y.D.S. Rajapakse. Durability of Composites in a Marine Environment, Springer, 2014.

Section 2.2

How durability can be addressed by the European Standard CEN/TS 19901:2022

CEN/TS 19101:2022 - Structure



TECHNICAL SPECIFICATION
SPÉCIFICATION TECHNIQUE
TECHNISCHE SPEZIFIKATION

CEN/TS 19101

November 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.

PUBLISHED

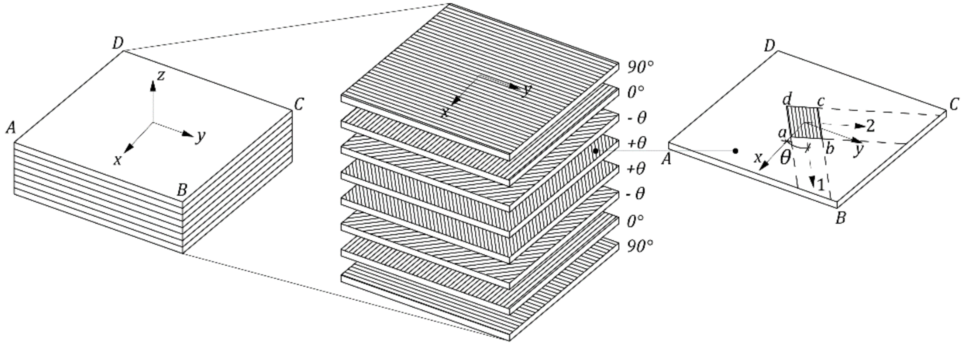
EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

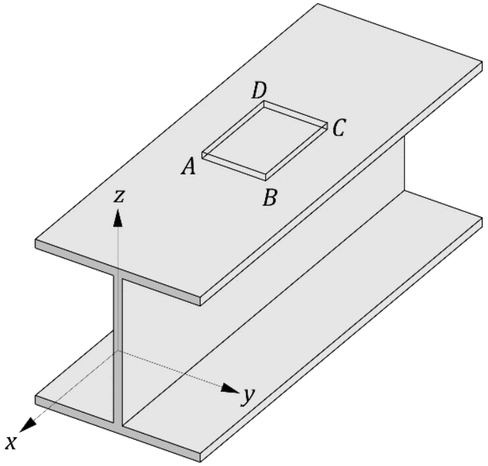
CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

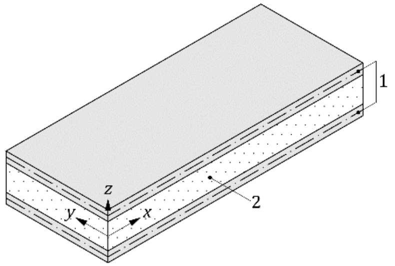
Ref. No. CEN/TS 19101:2022 E

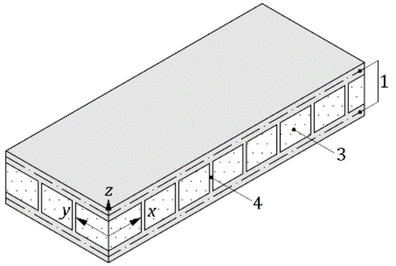
CEN/TS 19101:2022 - Scope

- The TS is 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









How durability can be addressed by the codes - CEN/TS 19101: 2022

- Therefore, **nominal conversion factors** that account for the **effects of temperature and moisture** on **material properties** are included in **the European Technical Specification (TS) FprCEN/TS 19101 Design of Fibre-Polymer Composite Structures**, for i) **composite materials**, ii) **sandwich core materials** and iii) **epoxy adhesives**.

- The **design resistances:**

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

Composite components, and members, bolted connections and joints

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

Creep rupture, fatigue, adhesive connections, and fire

How durability can be addressed by the codes - CEN/TS 19101: 2022

❑ Format of the design considering temperature and moisture effects

- 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:

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

Conversion factor for **temperature effects**

Conversion factor for **moisture effects**

η_{ct} accounts for **short-term changes** due to temperature effect

η_{cm} accounts for **changes due to moisture absorption over time**, including ageing effects resulting from **long-term exposure**, **for specific environmental conditions and a <u>50-year service life</u>**

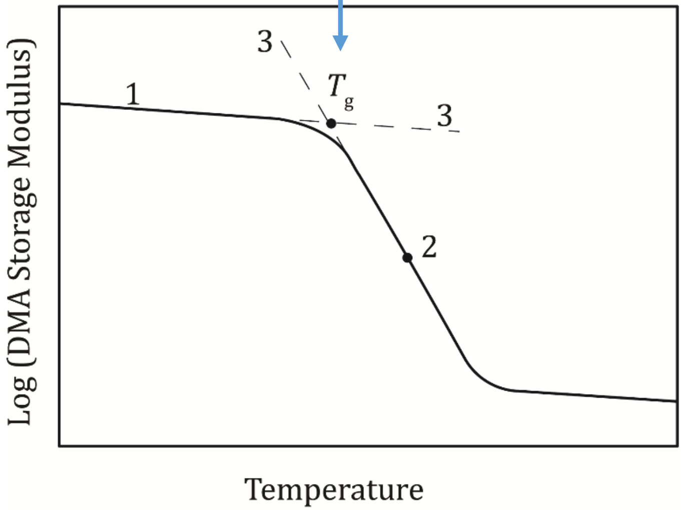
How durability can be addressed by the codes - CEN/TS 19101: 2022

❑ Format of the design considering temperature and moisture effects

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

$$-40\ °\mathrm{C} < T_s < T_g - 20\ °\mathrm{C}$$

The glass transition temperature (T_g) of composite, polymeric core and adhesive materials according to the TS (ISO 6721-11):



How durability can be addressed by the codes - CEN/TS 19101: 2022

❑ Format of the design considering temperature and moisture effects

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

$$-40\ °\mathrm{C} < T_s < T_g - 20\ °\mathrm{C}$$

Rationale:

- The imposed **lower bound** (-40 °C $< T_s$) → literature shows **limited reductions** in different mechanical properties at **sub-zero temperatures down** to -40 °C
- The imposed **upper bound** ($T_s < T_g - 20$ °C) → **relevant reduction in the short-term mechanical properties** and the **significant increase in viscoelasticity of composites, cores and adhesive materials** when temperatures approach the T_g.

How durability can be addressed by the codes - CEN/TS 19101: 2022

❑ Conversion factor for temperature

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

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

Example: what are the variation of the properties of a composite (T_g=100 °C) submitted to a service temperature of 50 °C?

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 can be addressed by the codes - CEN/TS 19101: 2022

❑ Conversion factor for moisture

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**:

Example: what are the variation of the properties of a composite (T_g=100 °C) submitted to a service temperature of 50 °C under outdoor exposure?

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**

Section 3

Viscoelasticity

Section 3.1

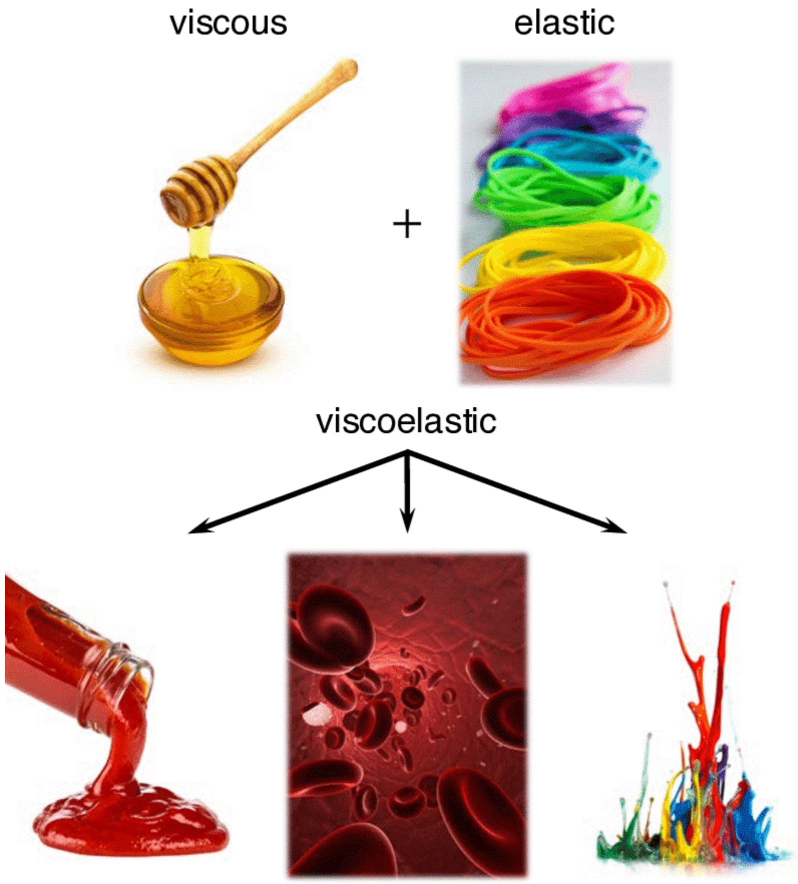
Introduction

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.

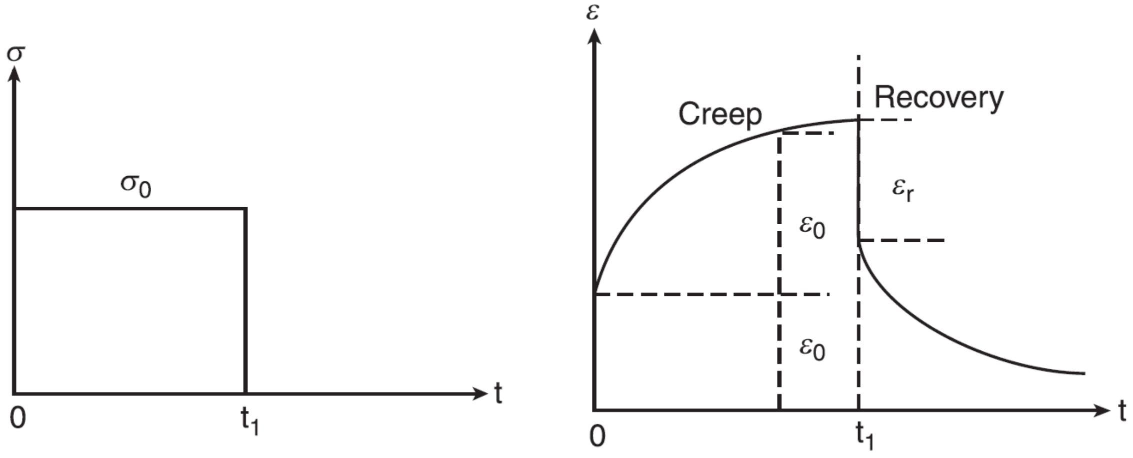
  - An **elastic material deforms instantaneously when stressed** and ‘remembers’ its original configuration, returning instantaneously to its original state once the stress is removed.



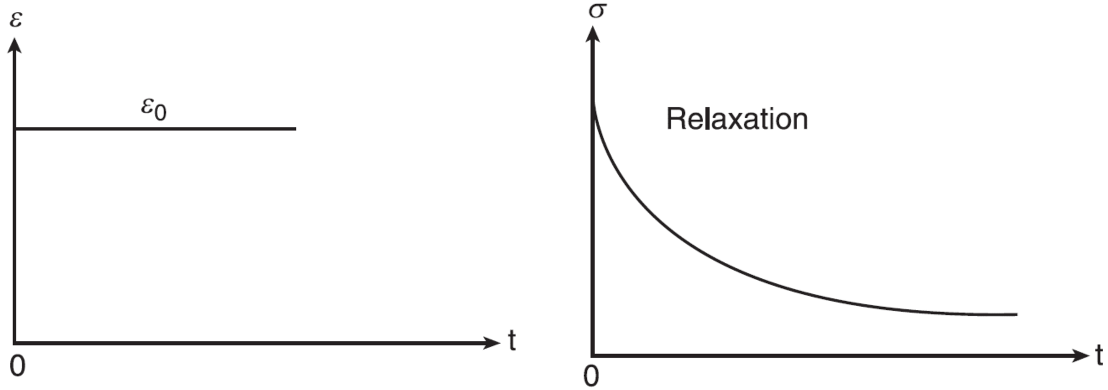
Source: J Berner. Out of Equilibrium Dynamics of Driven Colloids in Viscoelastic Media. Dissertation for the degree of Doctor of Natural Sciences, University of Konstanz, 2020.

What is Creep? What is Relaxation?

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

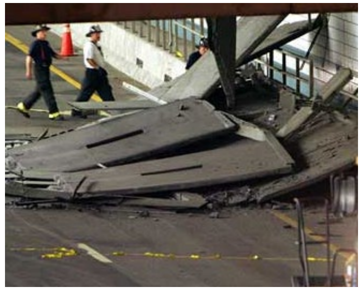


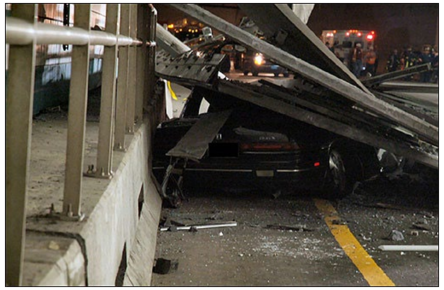
- **Relaxation** is a **gradual** and **continuous stress decrease** under **constant strain**.

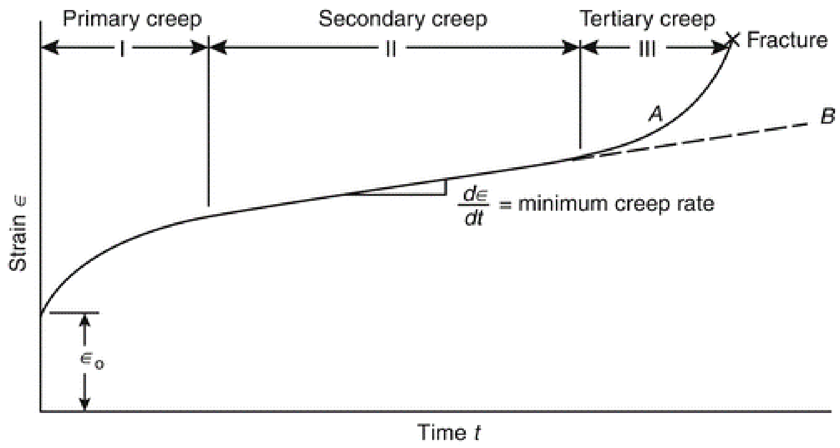


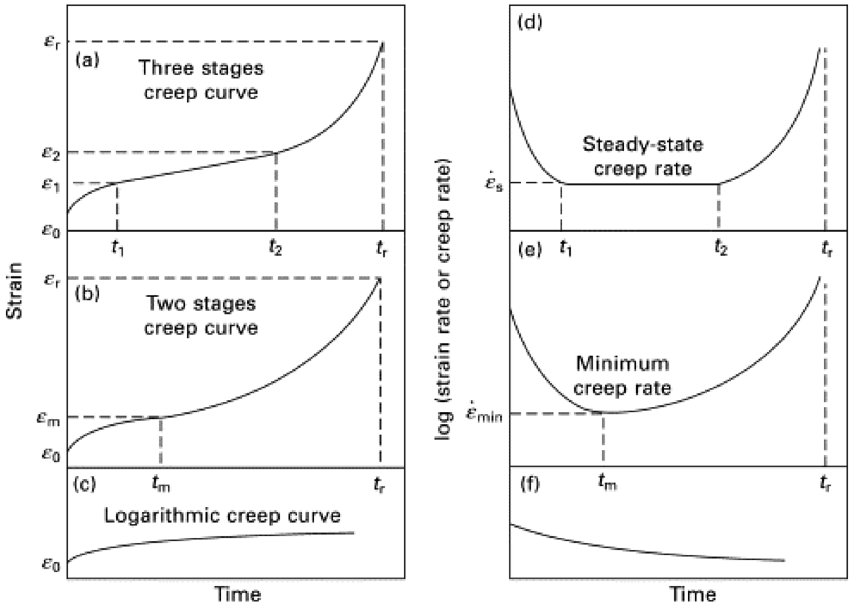
Creep stages

- **Primary creep**: the material undergoes deformation at a decreasing rate
- **Secondary creep**: the material progresses at a nearly constant rate
- **Tertiary creep**: it occurs at an increasing rate and ends with **fracture** of the material



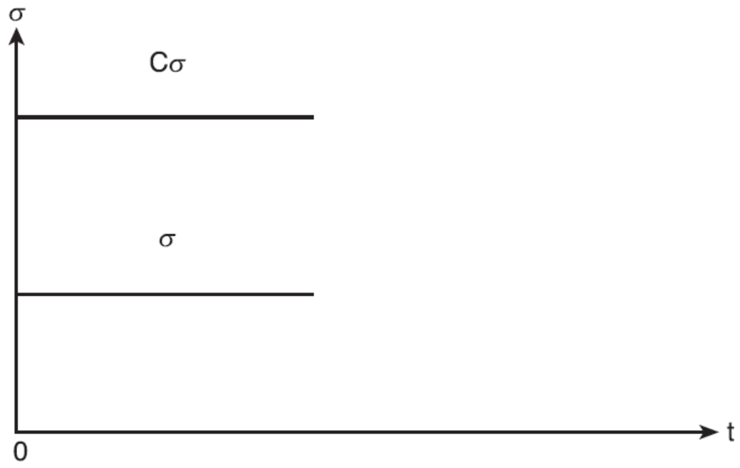






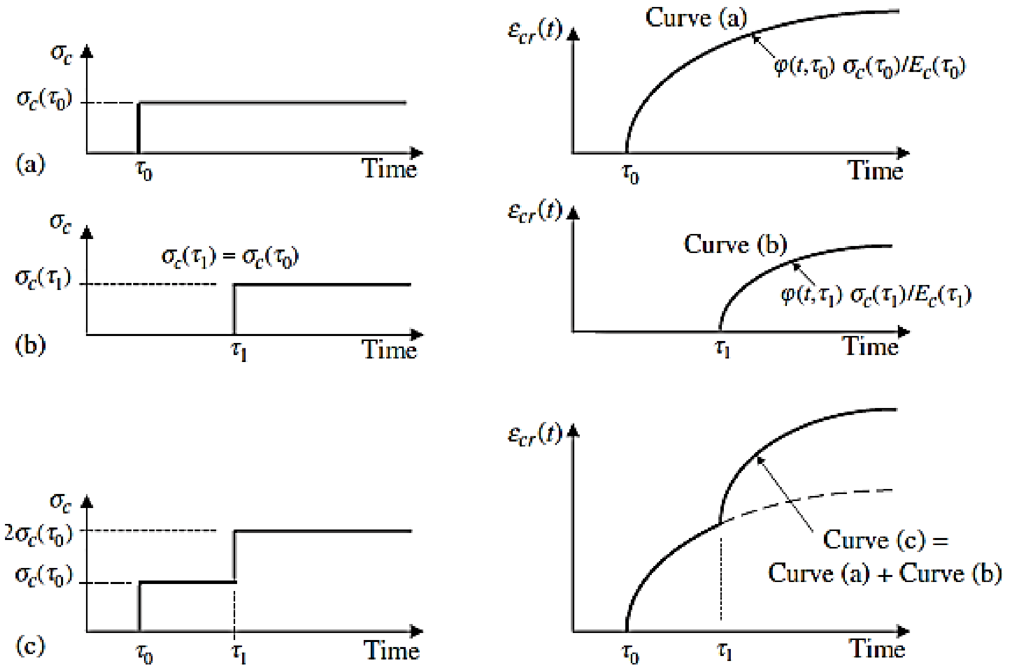
Linearity in creep: Homogeneity + Superposition Principle

Homogeneity



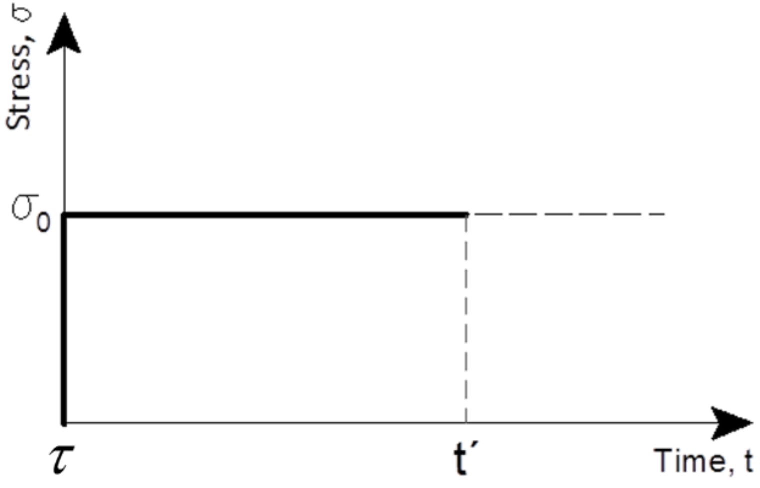
$$\varepsilon_x\left\{c\sigma_x\right\} = c\varepsilon_x\left\{\sigma_x\right\}$$
$$c = const$$

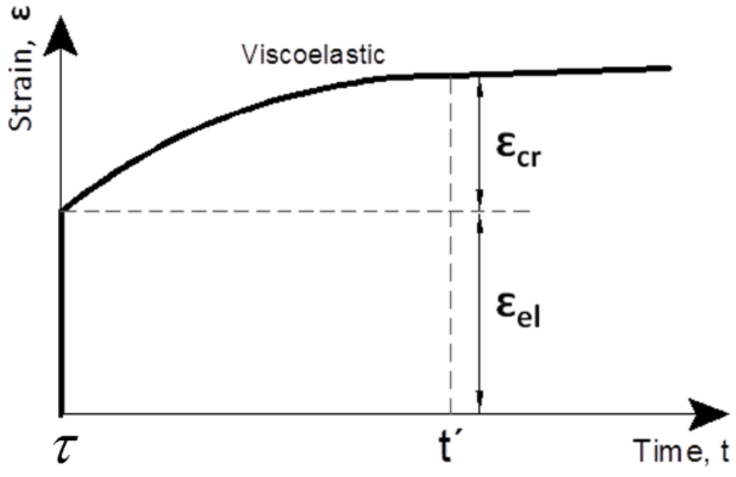
Superposition Principle



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

Creep: Creep coefficient ($\phi(t)$)





$$\phi(t) = \frac{\delta_{\text{creep}}(t)}{\delta_{\text{elast}}}$$

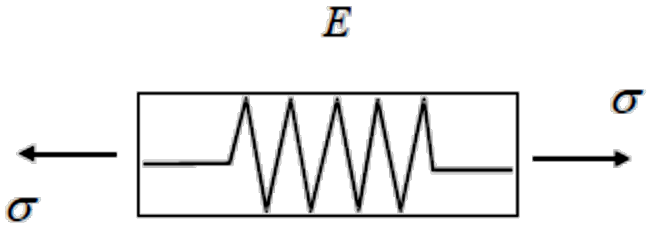
$$\delta(t) = \delta_{\text{elast}} + \delta_{\text{creep}}(t) \rightarrow \delta(t) = \delta_{\text{elast}} \cdot \left(1 + \phi(t)\right)$$

$$\delta = \frac{Const.}{E} \rightarrow \delta(t) = \frac{Const.}{E_{\text{elast}}} \cdot \left(1 + \phi(t)\right) = \frac{Const.}{\frac{E_{\text{elast}}}{1+\phi(t)}} = \frac{Const.}{E(t)}$$

$$E(t) = \frac{E_{\text{elast}}}{1 + \phi(t)}$$

Rheological Models: Basic components

Linear elastic spring

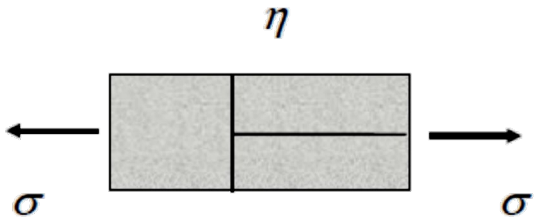


Hooke Model – typical of solids

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

ε – deformation, strain
E – elastic modulus

Linear viscous dash-pot



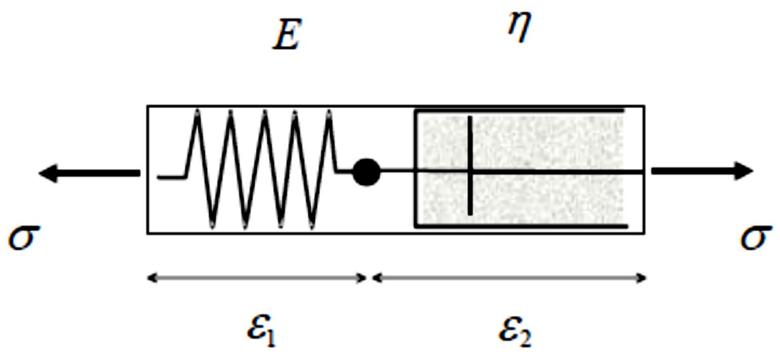
Newton Model – typical of flows

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

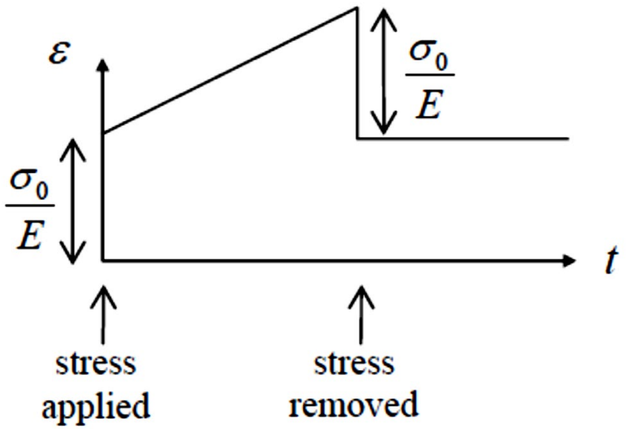
σ – stress applied
η – viscosity

Rheological Models: Basic components

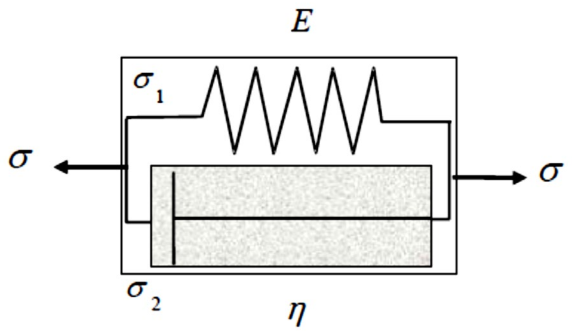
Maxwell fluid model



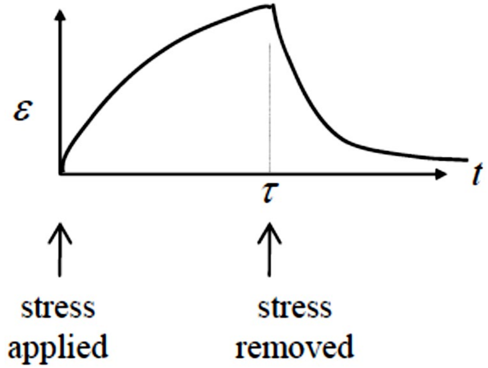
$$\dot{\varepsilon}(t) = \frac{\dot{\sigma}(t)}{E} + \frac{\sigma(t)}{\eta}$$



Kelvin (Voigt) solid model

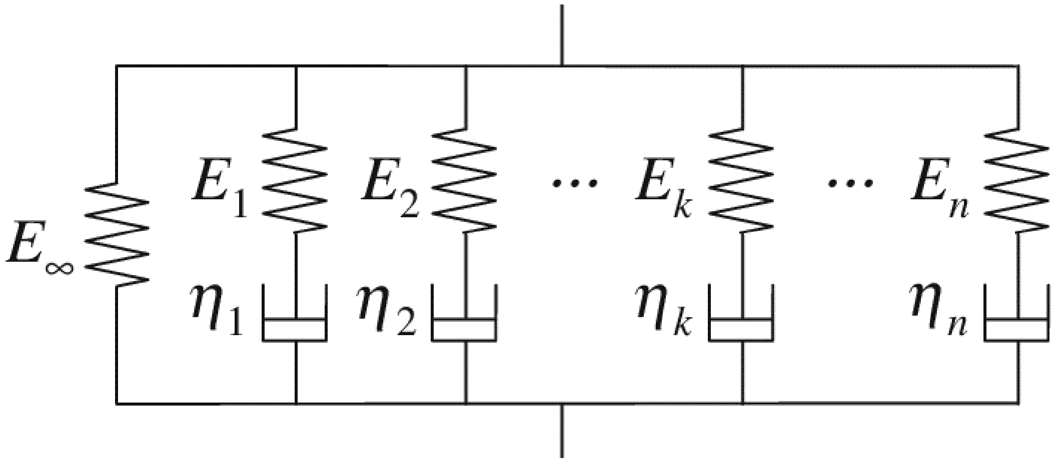


$$\dot{\varepsilon}(t) = \frac{\sigma(t)}{\eta} + \frac{E \cdot \varepsilon(t)}{\eta}$$

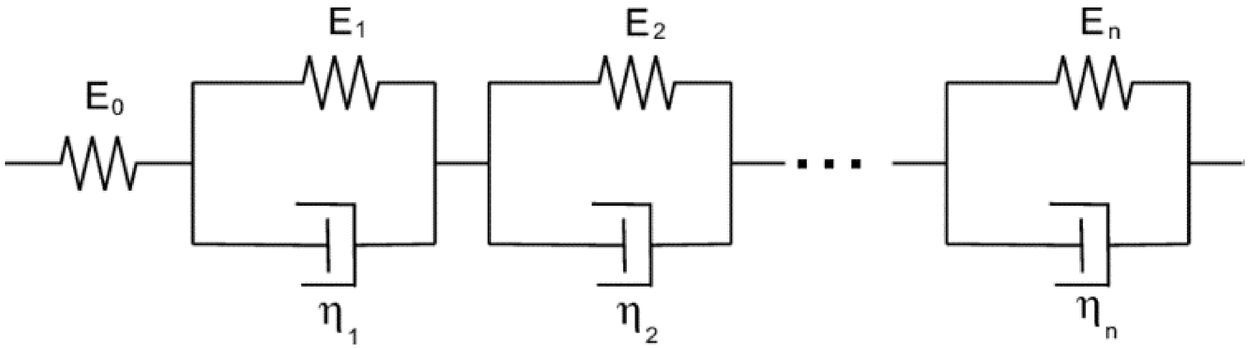


Rheological Models

Maxwell generalized model



Kelvin generalized model



Creep Model for Composite Materials: Findley's power law

time

Coefficient (material dependent for a given hygrothermal condition)

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

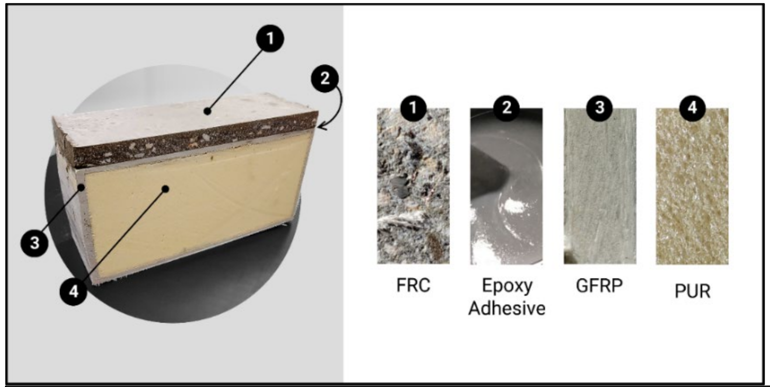
Displacement/strain during the time

time unit

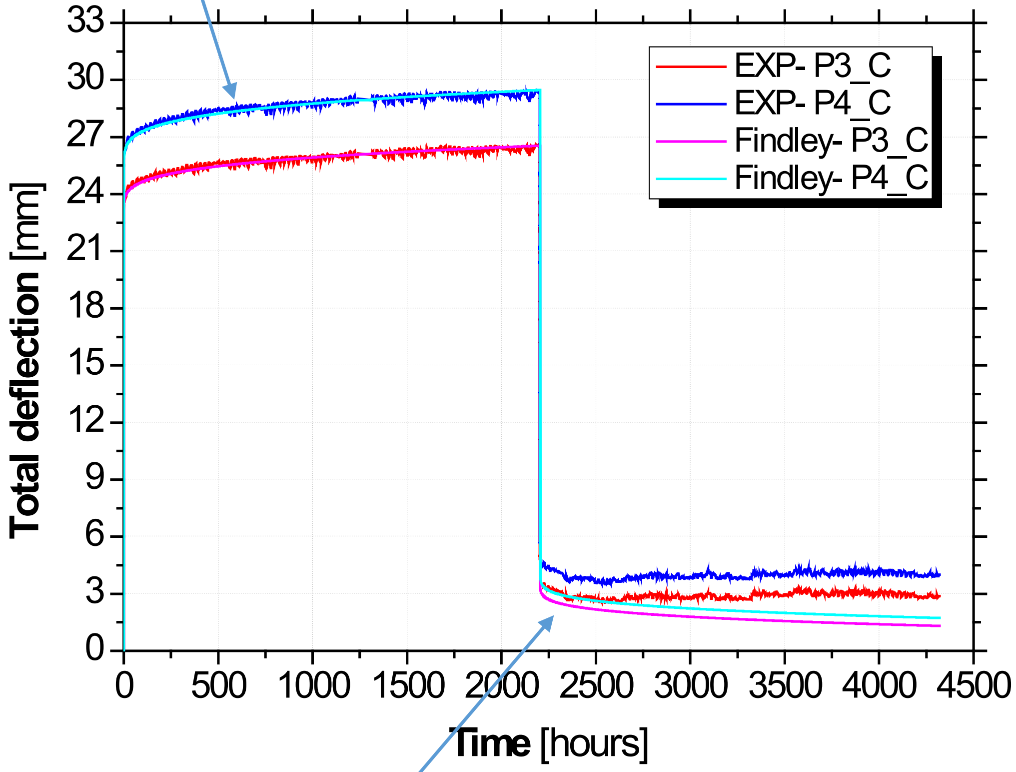
Elastic displacement/ strain

Creep amplitude coefficient (applied stress dependent)

Creep Model for Composite Materials: Findley's power law



$$\Delta(t) = \Delta_0 + m \cdot t^n$$



$$\Delta(t) = m \cdot (t_{un})^n + m_{un} \cdot (t - t_{un})^n$$

Source: Silva, T.; Correia, L.; Dehshirizadeh, M.; Sena-Cruz, J. (2022) "Flexural Creep Response of Hybrid GFRP–FRC Sandwich Panels." Materials, 15: 2536, 25 pp. DOI: 10.3390/ma15072536

Creep in composites

- The **creep in composites depends on several factors**, including:
  - The **environmental conditions** (temperature and relative humidity)
  - The **type of loading**
  - The **stress level**

- For **composite sandwich panels**, creep **deformations due to shear** are generally **more significant than those due to bending**, especially in homogeneous-core sandwich panels.

- For **composite materials** **and** **polymeric foam core materials**, in general, **linear viscoelasticity applies for relatively low stresses** (for composite materials with glass fibres, typically up to **25% to 30% of the short-term strength**).

Source: CEN/TS 19101: 2022 (E)

Creep in composites

- In general, the **viscoelasticity of composite, core and adhesive materials increases** with **increasing temperature and relative humidity**.

- For composite materials, the **creep coefficient decreases** with **increasing fibre content along the direction of the applied stresses**.

- For **polymeric foam core materials**, the **creep coefficient generally decreases with increasing density**, while for end-grain balsa the creep coefficient is independent of density.

- In addition, the **creep behaviour of polymeric foam core materials is generally orthotropic**.

Source: CEN/TS 19101: 2022 (E)

Section 3.2

How creep can be addressed by the CEN/TS 19901:2022

How creep can be addressed by the codes - CEN/TS 19101:2022

❑ 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 can be addressed by the codes - CEN/TS 19101: 2022

- 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

Source: CEN/TS 19101: 2022

How creep can be addressed by the codes - CEN/TS 19101: 2022

- Serviceability verification (Linear creep)

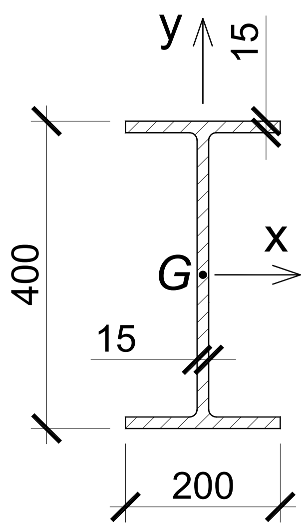
Table A.2 — Values for the creep coefficient, $\phi(t)$, for different elastic moduli of composite laminates/plies (glass, carbon or basalt fibres; fibre volume fraction of at least 35%; temperature up to 25 °C; relative humidity up to 65%)

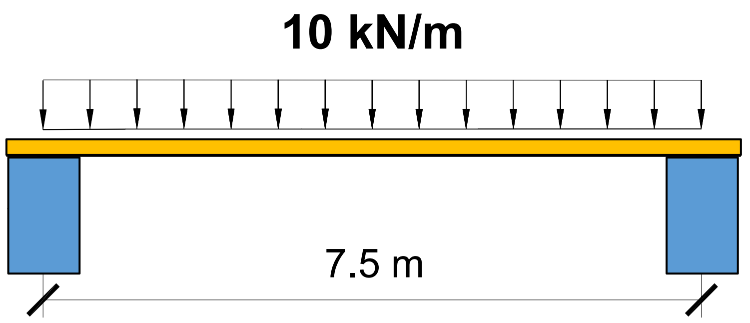
Type of fibres	Property	Period of time (years)										
		1	5	10	15	20	25	30	40	50	75	100
UD	$E_{x,t}$	0,10	0,11	0,12	0,13	0,13	0,13	0,13	0,14	0,14	0,14	0,15
	$E_{x,c}$	0,15	0,23	0,27	0,30	0,32	0,34	0,36	0,38	0,41	0,45	0,48
	G_{xy}	1,13	1,55	1,78	1,94	2,06	2,16	2,25	2,40	2,52	2,78	2,94
Woven (0/90°)	$E_{x,t}$, $E_{x,c}$	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

Source: CEN/TS 19101: 2022

How creep can be addressed by the codes - CEN/TS 19101: 2022

❑ Serviceability verification (Linear creep)





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

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

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

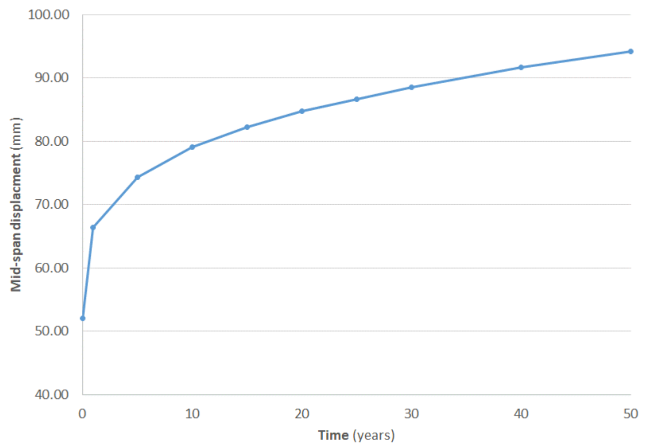
Pultruded GFRP I400 profile:

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

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 CEN/TS 19101: 2022)



How creep can be addressed by the codes - CEN/TS 19101: 2022

❑ Ultimate verification (Creep rupture)

Creep rupture of composite members and components **can be prevented by limiting sustained stresses, under the quasi-permanent combination of actions,** as follows:

Traction

$$\boxed{\sigma_{\mathrm{t,creep,Ed}} \leq \sigma_{\mathrm{t,creep,Rd}}}$$

$$\sigma_{\mathrm{t,creep,Rd}} = \frac{\eta_{\mathrm{c}}}{\underbrace{\gamma_{\mathrm{M,creep}}}_{(=1{,}5)}} \cdot k_{\mathrm{t,creep}} \cdot f_{i,\mathrm{t,k}}$$

Compression

$$\boxed{\sigma_{\mathrm{c,creep,Ed}} \leq \sigma_{\mathrm{c,creep,Rd}}}$$

$$\sigma_{\mathrm{c,creep,Rd}} = \frac{\eta_{\mathrm{c}}}{\underbrace{\gamma_{\mathrm{M,creep}}}_{(=1{,}5)}} \cdot k_{\mathrm{c,creep}} \cdot f_{i,\mathrm{c,k}}$$

How creep can be addressed by the codes - CEN/TS 19101: 2022

❑ Ultimate verification (Creep rupture)

Strength reduction factors ($k_{\mathrm{t,creep}}$ and $k_{\mathrm{c,creep}}$) for 50 years:

Type of stress	Glass	Aramid	Basalt	Carbon
Tensile	0.4	0.5	0.6	0.9
Compressive	**0.75×**0.4	**0.75×**0.5	**0.75×**0.6	**0.75×**0.9

& Anastasios P.Vassilopoulos

- G, A, C: strength reduction factors derived from an extensive literature review
- B: reduced existing data + engineering judgement
- A, B, C: values also valid for 100 years
- G: $k_{\mathrm{t,creep}}(t) = 0.9 - 0.088 \cdot \lg(t)$; $k_{\mathrm{c,creep}}(t) = 0.75 \cdot k_{\mathrm{t,creep}}(t)$
- $k_{\mathrm{c,creep}}$ = 0.75 × $k_{\mathrm{t,creep}}$: reduced existing data + engineering judgement

Many thanks!

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