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ABSTRACT

In November 2022, the European Committee for Standardization (CEN) published the Technical Specification CEN/TS 19101:2022, "Design of Fibre-Polymer Composite Structures", which is a milestone towards the widespread application of composite materials in civil engineering structures. This paper presents the basis of design of CEN/TS 19101:2022, which follows the philosophy and partial factor format of the Eurocodes, and describes how the effects of temperature and moisture are considered, namely through the use of conversion factors.

KEYWORDS

Fibre-polymer composites; European Technical Specification; Design code; Basis of design; Partial safety factors; Temperature; Moisture; Conversion factors.

INTRODUCTION

In 2010, the European Committee for Standardization (CEN) decided to develop a Eurocode for fibre-polymer composite structures. For that purpose, the Working Group "Fibre Reinforced Polymer" (WG4) was established by the Technical Committee 250 (TC250) of CEN. Between 2010 and 2016, members of WG4 developed a Science and Policy Report, "*Prospect for New Guidance in the Design of FRP*" (Ascione *et al*. 2016), the first step (of three) towards the development of the future Eurocode. Then, between July 2018 and October 2021, CEN/TC250 appointed a Project Team (WG4.T2) to develop the second step, the drafting of the Technical Specification (TS) CEN/TS 19101:2022, "Design of Fibre-Polymer Composite Structures", which was published in November 2022. After a period of trial use (usually two years), the TS is expected to be converted to a Eurocode.

CEN/TS 19101:2022 applies to buildings, bridges and other civil engineering structures, either permanent or temporary, providing a general basis for the design of all-composite structures or hybrid structures, combining composite members with members made of other materials. The TS covers three main types of composite components and members: (i) laminates (used, for instance, as plates or shells); (ii) profiles, and (iii) sandwich panels. These composite components can be made of different types of reinforcing fibres (glass, carbon, basalt, aramid) and thermoset polymeric matrices. Polymeric foams and balsa wood can be used as core materials of sandwich panels. With respect to connections, CEN/TS 19101:2022 applies to bolted, bonded (with thermoset adhesives) and hybrid connections.

This paper presents the information for the basis of design in CEN/TS 19101:2022 and describes how the effects of temperature and moisture are taken into account in design, through conversion factors. The first part of the paper describes the general format of resistance adopted in the TS and the way it

was particularized for specific types of Ultimate Limit State (ULS) design, namely for (i) composite components and members, and bolted connections and joints (resistance factor approach); and (ii) for creep rupture, fatigue, adhesive connections and fire (material factor approach). A summary of values of partial factors included in the TS is presented and the rationale for their definition is explained. The second part of the paper describes the methodology adopted to define the conversion factors that account for the effects of temperature and moisture on the material properties of composite materials, sandwich core materials and epoxy adhesives. The values of these factors were defined based on surveys of data available in the literature, and they take into account the material temperature and type of exposure in service conditions.

BASIS OF DESIGN

Partial factor format

CEN/TS 19101:2022 is based on the format of the Eurocodes, in which partial factors, conversion factors and characteristic values are used to determine conservative values, i.e. lower bound values for resistance and upper bound values for action-effects are used. This creates a margin that accounts for uncertainties in material properties, actions, geometry and models used to estimate resistance and action-effects. This margin is meant to ensure that most safety verifications result in design with a reliability index (β, a direct measure of the probability of failure) that is above a target acceptable level (β_{target}). Therefore, a design is deemed as safe as long as:

$$\beta \geq \beta_{target} \qquad \text{Eq. 1}$$

The reliability index depends on several concepts that are not discussed in this publication. Additional information can be found in EN 1990 and ISO 2394. For typical cases of ULS design, the value of β_{target} recommended in Annex C of EN 1990 for a reference period of 50 years is 3.8.

Before reliability concepts were introduced, structural codes were based on tradition and engineering judgment. In the Eurocodes and other present-day codes, a format for action-effect and resistance modelling is defined and partial factors are calibrated through reliability methods so that β_{target} is complied with in the majority of cases of ULS design. In the case of CEN/TS 19101:2022, since integration with the Eurocodes was intended:

- For action-effects, the formats and partial factors of the Eurocodes are used, see EN 1990;
- For resistance modelling, definition of resistance formats based on the Eurocode Design Value Format. This was followed by: (i) the determination of model uncertainties; and (ii) the calibration of partial factors using the methods of Annex C of EN 1990 and Annex D of ISO 2394.

The format for the design value of action-effects is common to the other Eurocodes and is not presented here. In the case of resistance modelling, both the resistance factor approach and the material factor approach are used. The next sections summarize the rationale behind the resistance format and partial factors used in CEN/TS 19101: 2022 for ultimate limit state design.

Design of composite components and members, and bolted connections and joints
Resistance format approach

The resistance factor approach is used in the design of composite components and members, and bolted connections and joints. The design value of resistance (R_d) is given by:

$$R_d = \frac{1}{\gamma_{Rd} \cdot \gamma_m} R\{\eta_{c,i} \cdot X_{k,i}; \, a_d; \Sigma F_{Ed}\} \qquad \text{Eq. 2}$$

where γ_{Rd} is the partial factor that accounts for the uncertainties in the resistance model and in the geometry, and γ_m is a partial factor that accounts for the unfavourable deviations of a representative material property from its characteristic value. $R\{...\}$ is the output of the resistance model, $X_{k,i}$ represents the characteristic values (5% fractile) of the material properties included in the resistance model, a_d

represents the design values of geometrical parameters, and i is for the ith material property. $\eta_{c,i}$ is the conversion factor for the effects of temperature and moisture, and is discussed later in this paper.

The representative material property used to define the value of γ_m is the material property whose uncertainty is governing for the overall uncertainty of the resistance. CEN/TS 19101:2022 states what is the representative material property for each failure mode.

This resistance factor approach is not the typical option adopted in the other Eurocodes, in which the partial factors for the uncertainties in strength (γ_m) and resistance modelling (γ_{Rd}) are jointly considered as a partial factor $\gamma_M = \gamma_m \times \gamma_{Rd}$. This format was chosen for CEN/TS 19101:2022 due to:
1. different possible materials, fibre content and layup and technology used to produce fibre-polymer composites;
2. differences in the model uncertainties (bias and precision) of the models used to estimate the resistance for the different failure modes;
3. a large number of material properties included in the resistance models - see the example for the face sheet wrinkling stress in direction i of sandwich panels, presented in Eq. (3), in which three material properties are used,

$$f_{i,\mathrm{wr}} = 0.65 \cdot \sqrt[3]{\left(E_{i,c}\right)_{\mathrm{f}} \cdot (E_{\mathrm{z}})_{\mathrm{c}} \cdot (G_{iz})_{\mathrm{c}}} \qquad \text{Eq. 3}$$

where $\left(E_{i,c}\right)_{\mathrm{f}}$ is the compressive modulus in the i direction of the face sheet, $(E_{\mathrm{z}})_{\mathrm{c}}$ is the out-of-plane elastic modulus of the core (the property used to define γ_m), and $(G_{iz})_{\mathrm{c}}$ is the out-of-plane shear modulus of the core.

These considerations imply that the resistance format needs to account: (i) for different values of γ_{Rd} for different failure modes; (ii) that a single representative material property is used to determine the value of partial factor γ_m; (iii) that the value of γ_m be defined based on the variability of the specific material(s) that will be used. The next sections explain how Eq. (3) complies with these conditions.

The resistance format presented in this subsection is meant for general applications. Alternative formats that jointly consider material and modelling uncertainties lead to more efficient and economical design, but test data for the specific structural system under analysis are required - see Annex D of EN 1990.

Partial factor for material properties
The Technical Specification CEN/TS 19101:2022 is a very particular case of a design document made for materials whose variability is not bound to a specific range. Traditional construction materials, such as concrete and steel, have a long-standing tradition and their production process is fairly similar across producers and regions. Therefore, the properties of these materials (and their variability) may be predicted adequately. Codes for the design of both steel and concrete structures follow a conservative assumption for the coefficient of variation of material properties that is applicable for steel and concrete products in general, this a single partial factor may be used for each material (in the case of reinforced concrete design, γ_C for concrete and γ_S for steel reinforcement).

This option is not satisfactory for fibre-polymer composites because the same specified characteristic value for a material property may, depending on the producer, correspond to very different mean values and coefficients of variation for the material property at stake because:
- fibre-polymer composites may be produced with different combinations of fibres (glass, carbon, basalt, aramid), polymeric resin (usually, polyester, vinylester or epoxy), fillers and additives;
- of differences in fibre layup, and in production technology and processing quality control.

The design of sandwich panels includes other materials in the core (usually polymeric foams and balsa wood), each also having different material variability. In bonded connections and joints, it is

necessary to account for the variability in the properties of adhesives. The variability of the material properties found in fibre-polymer composite structures design is discussed in the Commentary to CEN/TS 19101:2022 and in Pacheco *et al*. (2021).

The different variability of material properties due to differences in materials and producers is accounted for in CEN/TS 19101:2022 through a tabular format to be used by the designer. The designer uses the quality control records of the producer of the material and defines γ_m based on:
- selection of the representative material property for the failure mode under analysis;
- coefficient of variation (V_x) of the representative material property (Table 1);

In the absence of prior knowledge regarding V_x, a factor (f_{Vx}) shall be used before determining γ_m; this factor, which depends on the number of tests performed, is required to account for statistical uncertainty in material testing. Table 2 is used to find f_{Vx} based on the coefficient of variation of the tested sample, $V_{x,exp}$, then allowing to estimate V_x, i.e. $V_x = f_{Vx} V_{x,exp}$. Note that the processing quality control records are generally already available, since the producer needs them to define the characteristic value of the material properties of his products.

The rationale used to define γ_m, V_x and f_{Vx} is presented in the Commentary to CEN/TS 19101:2022 and in Pacheco *et al*. (2021). As justified in the Commentary to CEN/TS 19101:2022, Tables 1 and 2 assume that the representative material property is lognormal-distributed.

Table 1: Definition of γ_m from the coefficient of variation of the representative material property (V_x)

V_x	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
γ_m	1.07	1.15	1.23	1.32	1.41	1.51	1.61	1.71	1.82

Table 2: Factor f_{Vx} to account for statistical uncertainty of V_x (to be used when V_x is unknown)

Number of samples	5	10	15	20	25	30	50	100	999
f_{V_x}	1.70	1.19	1.12	1.08	1.07	1.05	1.03	1.02	1.00

Partial factor for resistance models

The partial factor for resistance (γ_{Rd}) depends on the ULS failure mode, with the following values being recommended:
- γ_{Rd} for profiles and laminates:
  - Material failure: 1.40;
  - Global buckling, flexural buckling and lateral-torsional buckling: 1.30;
  - Global buckling, flexural-torsional buckling: 1.55;
  - Local buckling: 1.30.
- γ_{Rd} for bolted connections:
  - All cases (net-tension, pin-bearing, shear-out, block-shear and pull-out failures): 1.50.
- γ_{Rd} for sandwich panels:
  - Composite material failure: 1.40;
  - Core material failure: 1.50;
  - Global buckling: 1.40;
  - Local buckling: 1.30;
  - Face sheet/web wrinkling, core indentation, core punching failure: 1.50.

The derivation of each γ_{Rd} requires the determination of model uncertainties of resistance (θ_R) for each resistance model associated to these failure modes. For that, the methodology presented in Section C.6 of ISO 2394 and in Annex D of EN 1990 is used. A brief overview is presented here:
- Each failure mode corresponds to a resistance model considered in CEN/TS 19101:2022;
- Experiments concerning each failure mode are collected and validated (e.g. all properties required in the resistance model need to be stated; the mean values of the material properties

must be determined from testing; geometric and loading conditions are non-ambiguously stated and the experimental failure mode corresponds to that expected by the experiment);

- The resistance predicted by the resistance model is calculated for each result using all collected data concerning material properties, loading and geometry. Note that this calculation does not involve any characteristic values or partial factors, since the objective is to make an unbiased assessment of the resistance model;

- The ratio between the experimental resistance observed from each test result and that predicted by the resistance model, θ_R, is calculated as follows,

$$\theta_R = \frac{Experimental\ load-bearing\ capacity\ (x_i,\dots,x_j,a)}{R(x_i,\dots,x_j,a)} \qquad \text{Eq. 4}$$

where $R(x_i, \dots, x_j, a)$ is determined using the material properties for each test.

- The database of test results is analysed so that any trends between θ_R and input parameters of the model are detected (Figure 1 - left);

- Statistics (mean and standard deviation / coefficient of variation) and a probability distribution for the θ_R are defined. In general and irrespective of the structural material, θ_R is well-modelled by a lognormal distribution, since θ_R is a multiplicative variable (see Annex E of ISO2394);

- A preliminary γ_{Rd} is put forward based on assumptions (e.g. those of Annex D of EN 1990).

- Table 3 presents the θ_R found for (face sheet) wrinkling and core shear failure (in which flexible and rigid cores and distinguished) in sandwich panels. Additional information on the assessment of θ_R from experimental tests may be consulted in Holický *et al.* (2016).

Table 3: Statistics of the model uncertainty (θ_R) for resistance models used in sandwich panel design

Failure mode	Wrinkling failure	Flexible core shear failure	Rigid core shear failure
Number of test results	12	27	19
Mean (bias) θ_R	0.93	1.03	1.00
Standard deviation θ_R	0.19	0.22	0.3
Coefficient of variation θ_R	20%	21%	30%
Probability distribution	Lognormal	Lognormal	Lognormal

Table 3 shows that the resistance models are unbiased (mean θ_R close to 1.0), except in the case of wrinkling failure (whose resistance model tends to overestimate resistance), and less precise (higher coefficient of variation) than what is usually found in resistance models used in civil engineering. The relatively high coefficient of variation is a consequence of: (i) the different types of combination of materials used in sandwich panel design; (ii) the resistance models used for these failure models being semi-empirical; and (iii) the relatively small number of test results collected for these failure models. Lognormal distributions were checked for and fitted the data well. The findings presented here are not necessarily common to other ULS resistance models, but statistics for other resistance models are not presented in this communication for brevity's sake. They may be consulted in the Commentary to CEN/TS 19101:2022 and Sá *et al.* (2021).

As a next step, the preliminary estimate of γ_{Rd} is calculated for each resistance model. This step takes into account β_{target}, the service life (e.g. 50 years) of the structural design, and the relative importance of θ_R on the overall resistance uncertainty of the design. Then, the estimated γ_{Rd} is either calibrated based on reliability analysis or validated/changed based on engineering judgement (e.g. when information available is not sufficient). The aim of this step is ensuring that, for most cases of design, β_{target} is complied with. A simplified explanation of a reliability-based calibration process is now presented:

- Different cases of design are defined, covering different loading conditions, geometry and material properties (in the case of CEN/TS 19101:2022, different coefficients of variation were checked);

- Starting with the preliminary estimate of γ_{Rd}, the structural member of each case is designed;

- Reliability analyses are carried out to check whether β_{target} is complied with;

- These reliability analyses have to necessarily account for the influence of the variability of material properties on β – see Figure 1, right;
- The partial factor is iteratively changed until satisfactory compliance with β_{target} is found.

Note that no structural code can ensure that all cases of design comply with β_{target}, otherwise design would not be economical for the majority of situations. This is true because ensuring safety for very unlikely conditions (e.g. very high and unrepresentative ratios of variable load to total load) necessarily implies that the margin of safety for representative cases of design would need to increase to an unreasonable large extent. The calibration of the γ_{Rd} for global buckling of profiles can be consulted in Pacheco *et al.* (2021), in which additional explanations are provided.

In the case of calibration based on judgment, the main criterion was to adopt the same partial factors that were defined for similar failure modes (e.g. the partial factor for composite material failure of sandwich panels was assumed as equal to that used for profiles and laminates).
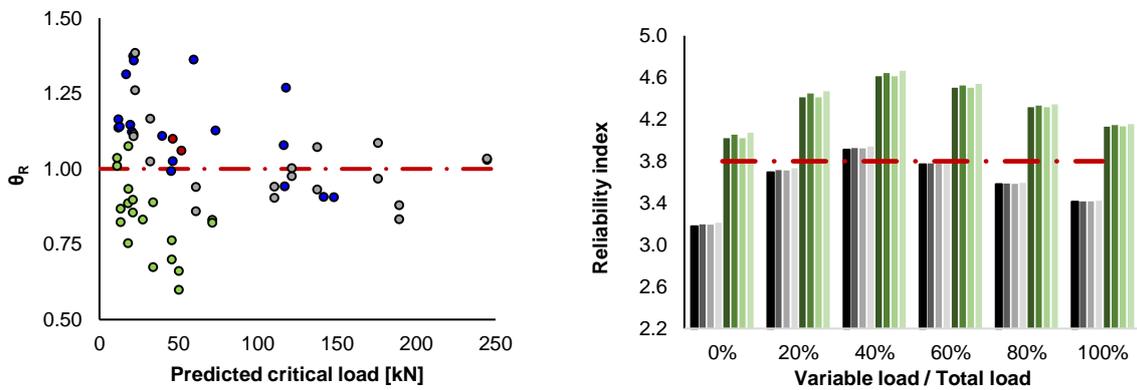

Figure 1: Left graph - Model uncertainties for flexural-torsional buckling of profiles; right graph - Reliability indices for 4 cases of design and two assumptions on the coefficient of variation of material properties: 5% (in grey) and 20% (in green). Results before calibration of partial factor γ_{Rd}

Design for creep rupture, fatigue, adhesive connections and fire
Resistance format and partial factor γ_M
The approach presented in the previous section could not be followed for creep rupture, fatigue, adhesive connections and fire design due to lack of experimental data. This lack of test results hinders differentiating between the partial factors γ_m and γ_{Rd}, as well as collecting datasets with sufficient information for partial factor calibration. Therefore, the material factor approach of EN 1990 was used and the design value of resistance in these cases is defined as:

$$R_{\text{d}} = R \left\{ \eta_{\text{c},i} \cdot \frac{X_{\text{k},i}}{\gamma_{\text{M}}} \; ; a_{\text{d}}; \Sigma F_{\text{Ed}} \right\} \qquad \text{Eq. 5}$$

where γ_M is the only partial factor used; this partial factor accounts for the uncertainty in the resistance model, as well as for unfavourable deviations in material properties and geometry.

The partial factors adopted in CEN/TS 19101:2022 are the following:
- $\gamma_{\text{M,fire}}$=1.0 for fire design, based on the fire parts of other Eurocodes;
- $\gamma_{\text{M,creep}}$=1.5 for creep rupture, based on the partial factors for material failure;
- $\gamma_{\text{M,f}}$, for fatigue, ranging from 1.5 to 3.0; this partial factor is based on a proposal in Eurocomp (Clarke, 1996) and on a plausibility check;
- $\gamma_{\text{M,ac}}$, for adhesive connections design, ranging from 1.5 to 2.5; a proposal in Eurocomp (Clarke, 1996) was also the basis for this partial factor.

These partial factors shall be verified as additional information and test results becomes available.

EFFECTS OF TEMPERATURE AND MOISTURE

Consideration of temperature and moisture effects

In CEN/TS 19101:2022, the conversion factor accounting for changes in the mechanical properties of composite materials (and sandwich core materials and adhesives) due to temperature and moisture effects, η_c, is given as a product of two factors:

$$\eta_c = \eta_{ct} \times \eta_{cm} \qquad \text{Eq. 6}$$

where η_{ct} and η_{cm} are respectively the conversion factors for temperature and moisture effects, defined in the following two sub-sections.

Eq. (6) is based on the assumption that the effects of temperature and moisture together can be determined by multiplying their individual effects. This assumption was made due to the present lack of a more reliable method (and test data) to analyse the combined environmental effects of temperature and moisture. Similar approaches have been used in other design guidelines for fibre-polymer composite structures (e.g. CNR-DT 2008, ASCE/ACMA 2010, BUeV 2014, CROW-CUR 2019) and also for other materials.

Conversion factor for temperature

The conversion factor for temperature, η_{ct}, accounts for reversible changes of material properties due to material temperatures in service conditions relative to the material properties at 20 °C, excluding irreversible effects of long-term exposure.

According to CEN/TS 19101:2022, the material temperatures in service conditions (determined based on climatic temperatures, as defined in EN 1991-1-5) should range between -40 °C and $T_g - 20$ °C, T_g being the glass transition temperature of the material, defined based on dynamic mechanical analysis (DMA), from the onset value of the storage modulus decay (as it provides a direct relation with the reduction in mechanical properties), in log scale; moreover, the T_g should be higher than 60 °C.

In this respect, it is important to emphasize the following points: (i) the upper limit for the material temperature under service conditions is defined as $T_g - 20$ °C and not as T_g, because significant reductions in mechanical properties are already observed when material temperature approaches T_g (in particular, for matrix-dominated properties); (ii) the impact of long-term exposure to such higher ambient temperatures is generally minimal as long as the material remains within the specified temperature range for service conditions and the matrix is adequately cured; (iii) prolonged exposure to higher temperatures below T_g typically leads to an improvement in the mechanical properties of polymeric materials due to post-curing effects (yet, conservatively, these positive effects countering deteriorations from durability effects are not accounted for by the conversion factor for temperature).

The mechanical properties of composite materials can be either fibre- or matrix-dominated properties, provided they have respectively low and high sensitivity to matrix softening as temperature approaches (and exceeds) T_g. Usually, tensile strength, tensile modulus and compressive modulus in direction(s) with relatively high fibre volume fraction in the load direction are fibre-dominated; on the other hand, tensile strength and modulus and compressive modulus in direction(s) with relatively low fibre volume fraction in the load direction, such as compressive strength, interlaminar shear strength, and in-plane shear strength and modulus are matrix-dominated.

For composite materials, the conversion factor for temperature is defined as follows,

$$\eta_{ct} = \min\left\{1 - \alpha \cdot \frac{T_s - 20°C}{T_g - 20°C}; 1.0\right\} \qquad \text{Eq. 7}$$

where T_s is the maximum service temperature experienced by the composite material in service conditions (temperature in the material) and α is a parameter that was defined (calibrated) based on

the survey of test data available in the literature, as detailed below. For composite materials with glass, carbon or basalt fibres and thermoset polymer matrix of either unsaturated polyester, vinylester or epoxy, $\alpha = 0.25$ and $\alpha = 0.80$ for respectively fibre-dominated and matrix-dominated properties.

It should be noted that Eq. (7) does not account for the possible increase of mechanical properties at service temperatures below 20 ℃. This is primarily due to the scarcity of available test data within this temperature range. Despite the increased brittleness observed at lower temperatures, existing literature on the mechanical properties of composite materials at sub-zero temperatures indicates either a moderate increase or a slight reduction in elastic moduli and strength, down to the minimum service temperature of -40 ℃.

The values of α referred to above were defined based on a survey of test data available in the literature concerning mechanical tests at elevated temperature in composite materials with different shapes (profiles, laminates, bars), produced by different composite processing methods (pultrusion, hand layup, vacuum infusion), comprising different types of fibres (glass, carbon, basalt) and polymer matrices (polyester, vinylester, epoxy, urethane acrylate), and subjected to different types of mechanical tests (tension, compression, in-plane shear and interlaminar shear). In the 21 studies that were considered (reviewed in detail in Correia *et al*. 2023), mechanical characterisation tests (251 test results, each corresponding to an average of several replicate specimens) were usually performed in steady state conditions; this means that the material was heated to a specific target temperature (without any mechanical loading) and, after a relatively short soaking period (usually less than 1 hour), it was tested at constant temperature. Consequently, these test results do not account for the long-term effects of exposure to the target temperature.

The following requirements were set for database inclusion: (i) the reference material properties had to be determined at room temperature (~20 ℃) or under standard atmospheric conditions, using standardized test methods; (ii) the T_g of the composite material had to be provided and, in principle, determined from DMA testing, based on the onset value of the storage modulus decay (as defined in CEN/TS 19101:2022); (iii) the failure modes at elevated temperatures had to remain consistent with those observed at room temperature.

In order to determine the parameter α in Eq. (7), two criteria were taken into account. Firstly, Eq. (7) had to yield conservative estimates for over 90% of the experimental test results analysed. Secondly, for the test results that were overestimated, Eq. (7) had to provide reasonably low maximum relative differences compared to test data, with a specified threshold of 15%. The parameter α was determined through an iterative process that aimed to identify the minimum value satisfying both conditions mentioned earlier, while the selection of the 90% and 15% thresholds was based on engineering judgement. Statistical or reliability considerations, such as those outlined in EN 1990, were not used due to insufficient experimental data available.

Figure 2 compares test results with equivalent predicted values of remaining (or normalized) fibre- and matrix-dominated properties by applying Equation (7) with the values of parameter α indicated above.

For fibre-dominated properties, the results exhibit relatively low scatter (coefficient of variation of the bias of 7%); moreover, only 5% of the test data are overestimated, with a minimum bias of 0.88. In contrast, matrix-dominated properties demonstrate relatively higher scatter (coefficient of variation of the bias of 38%). Although 9% of the test data are non-conservatively overestimated, the minimum bias is 0.98; in other words, the relative differences between predictions and test results are nearly negligible for the few cases of overestimation. The increased scatter in estimating matrix-dominated properties can be attributed to the following factors: (i) The larger number of properties considered within this category; (ii) The intrinsic higher complexity of matrix-dominated properties, particularly the compressive strength and the in-plane shear strength; and (iii) The difficulty involved in testing these properties (at both ambient and elevated temperatures), as well as the use of different test methods to determine a specific property.
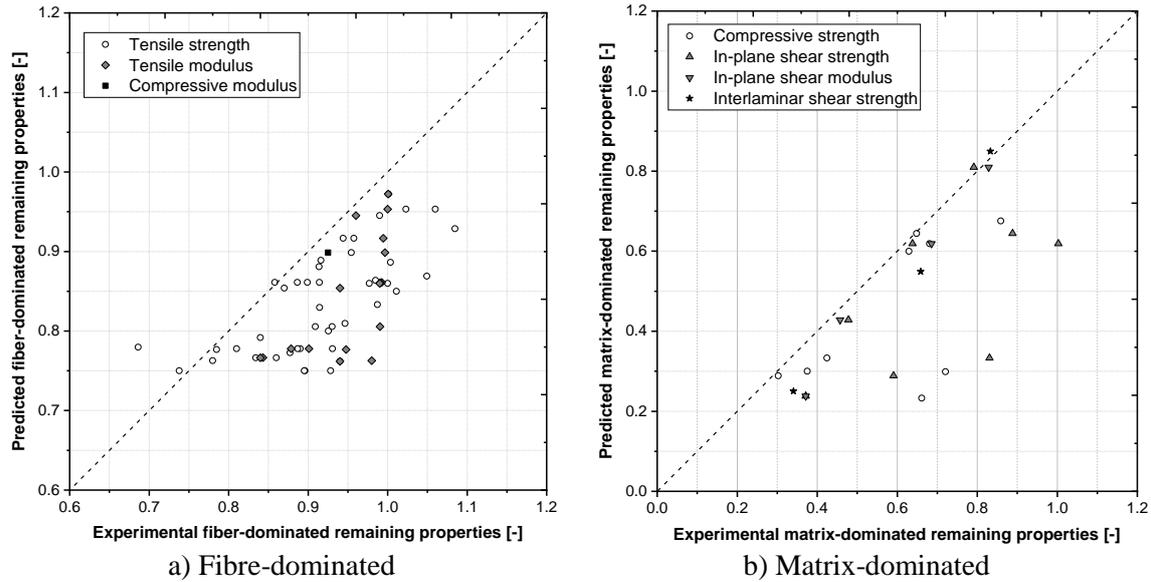
a) Fibre-dominated   b) Matrix-dominated

Figure 2: Predicted *vs.* experimental remaining (normalised) mechanical properties at elevated temperature of composite materials

CEN/TS 19101:2022 also provides temperature conversion factors for polymeric foams and balsa wood, used in sandwich panels as core materials, and for epoxy adhesives, used in load bearing bonded connections and joints. The values of those factors were defined following a similar approach to that described above for composite materials.

Further details about the definition of the values of the conversion factor for temperature are given in the Commentary to CEN/TS 19101:2022 and in Correia *et al.* (2023).

Conversion factor for moisture
The conversion factor for moisture, η_{cm}, accounts for changes of material properties due to moisture absorption over time, including ageing effects resulting from long-term exposure. To apply the conversion factor for moisture, the following three exposure classes are defined in CEN/TS 19101:2022: (i) Class I - Indoor exposure; (ii) Class II - Outdoors exposure without continuous exposure to water, or permanent immersion in water, or permanent exposure to a relative humidity higher than 80%, or combined UV-radiation and frequent freeze-thaw cycles; and (iii) Class 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).

For unprotected composite materials (with glass, carbon or basalt fibres; thermoset unsaturated polyester, vinylester or epoxy resin matrices; and overall fibre volume fraction of at least 35%), the following values of the conversion factor for moisture were adopted for each exposure class: Class I: $\eta_{cm} = 1.00$; Class II: $\eta_{cm} = 0.85$; Class III: $\eta_{cm} = 0.60$.

For Class I (indoor exposure), it was assumed that the mechanical properties of the above-mentioned types of composite materials are not negatively affected. For Class II and Class III, the above-mentioned values of the conversion factor for moisture were defined based on a survey of data available in the literature and, once again, on engineering judgement, considering the percentage of non-conservative estimates, and the maximum and the average values of the relative differences between the conversion factor that was set and non-conservatively estimated data points.

For Class II, the conversion factor for moisture of composite materials was determined based on 10 studies, which involved a total of 211 data points (each representing an average value). These studies examined the impact of natural outdoor weathering on the mechanical properties (in tension, flexure,

shear and interlaminar shear) of composites produced with glass fibre reinforcement and featuring different key characteristics: resin (unsaturated polyester, vinylester), shape (laminates or profiles), manufacturing process (pultrusion, vacuum infusion, hand layup), and fibre volume fraction (33% to 60%). The following exposure environments were considered, with durations up to 20 years: Alpine (Switzerland); humid continental (Maine, USA); Mediterranean (Lisbon); semi-continental (Milan); temperate oceanic (Rotterdam); temperate (Kyoto); indoor (with relatively high relative humidity at 23 ºC, thus included).

Figure 3 presents the data collected in this survey for Class II, namely the property retention as a function of the exposure period; this plot does not take into account the specific properties or characteristics of the materials nor the exposure environments. The lowest property retention values range from 60% to 65%, while a few results indicate property increases of up to 40% compared to the initial properties (attributed to the positive effect on properties of post-curing). No clear trend of property reduction with increasing exposure time is observed. It is worth noting that the longest exposure period considered in this survey is 20 years, which is relatively short when considering the typical service life of civil engineering structures (50 or 100 years).
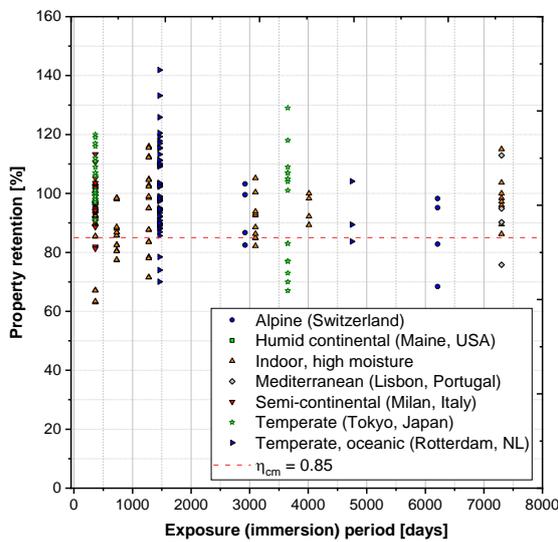

Figure 3: Remaining (normalized) mechanical properties *vs*. exposure period for natural (outdoor) weathering (Class II)
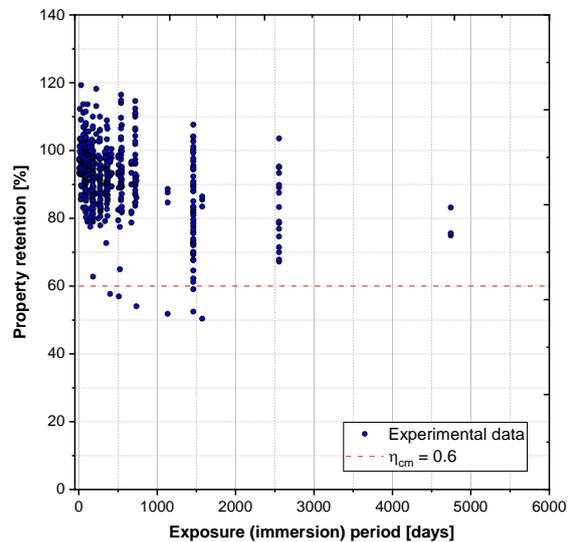
Figure 4: Remaining (normalized) mechanical properties *vs*. exposure period for immersion (Class III)

By adopting a value of $\eta_{cm} = 0.85$ for Class II, approximately 17.5% of the data points collected from the database exhibit higher degradation levels than predicted by such conversion factor; moreover, the maximum and average relative differences between such experimental results and predictions are relatively small, approximately 22% and 8%, respectively. Sorting the data plotted in Figure 3 by type of climate did not reveal clear differences in property retention between the different climates, possibly due to the limited number of data points and the variety of exposure periods within each subset of data (yet, some differences could be identified, as expected). Sorting the data plotted in Figure 3 by resin type (unsaturated polyester *vs*. vinylester) or by type of property (strength *vs*. elastic moduli) also did not indicate substantial differences in property retention trend over time of exposure to justify a differentiation in the values of the conversion factor for moisture; this is also likely due to the relatively limited number of data points.

For Class III, the conversion factor for moisture of composite materials was determined based on 18 studies, which involved a total of 516 data points (each representing an average value). These studies assessed the effects of immersion (at 20 ºC) up to ~5000 days (~14 years) on the mechanical properties (in tension, flexure, shear and interlaminar shear) of composites produced with glass fibre reinforcement and featuring different key characteristics: type of resin (polyester, vinylester), shape

(laminates or profiles), manufacturing process (pultrusion, vacuum infusion, hand layup), fibre volume fraction (32% to 62%), immersion media (water, seawater, saline solution). The survey also included six studies in which the Arrhenius law was used to predict (extrapolate) the retention of mechanical properties up to 100 years.

Figure 4 presents the data collected in this survey for Class III, namely the property retention as a function of the exposure period; this plot does not differentiate the type of mechanical properties, the characteristics of the materials or the type of immersion medium. Data was obtained for exposure durations of ~14 years, yet there is a scarcity of data points for exposure periods exceeding 8 years. The retention values reach a minimum of around 50%, but some data points indicate property increases (up to 20%), even after prolonged exposure to moisture (attributed to post-curing). However, as expected, a noticeable overall trend of decreasing property retention with longer exposure periods can be observed.

When a value of $\eta_{cm} = 0.60$ is adopted, 1.4% of data points of the database present higher degradation than that accounted for by the conversion factor. Furthermore, the maximum and average relative differences between such results and the corresponding estimates are relatively low, around 10% and 5%, respectively. Because test data was only available for a relatively short duration of immersion exposure, the value defined for the conversion factor was further assessed by considering the Arrhenius-based long-term predictions; such a relevant comparison seems to support the class III value of η_{cm} adopted. As for Class II, an attempt was also made to sort the data plotted in Figure 4, in this case by type of resin (unsaturated polyester *vs.* vinylester) and type of property (strength *vs.* elastic moduli). Although revealing some differences in performance, such branching of the test data did not permit differentiated values for the conversion factor for moisture.

Further information about the definition of the values of the conversion factor for moisture is available in the Commentary to CEN/TS 19101:2022 and in Garrido *et al*. (2022).

CONCLUDING REMARKS

The first part of this paper presented the resistance formats and partial factors used to calculate the design value of resistance for ultimate limit state design according to CEN/TS 19101:2022. The methodologies and rationale adopted are common to the other Eurocodes: resistance models and resistance formats are defined, and partial factors and conversion factors are either calibrated based on reliability and statistical analysis or, in the absence of information, engineering judgment is used.

Due to wide range of production processes and material combinations found in fibre-polymer composites design, the resistance factor approach is used for most cases of ultimate limit state design. A tabular format is used by the designer to determine the partial factor for material properties (γ_m) based on the coefficient of variation of a representative material property, determined from test records of the producer. Different partial factors for the uncertainty in resistance and geometry (γ_{Rd}) are presented in the code, each for a specific failure mode. The material factor approach and expert judgement were used for particular cases of design (fire, creep rupture, adhesive connections and fatigue) due to the scarcity of test results. Expert judgment was based on the options in other Eurocodes and in the Eurocomp design code and the options taken are to be validated when additional information is available.

The second part of this paper summarized the approach adopted in CEN/TS 19101:2022 to establish the conversion factors that take into account the influence of temperature and moisture on the properties of composite materials. The methodology adopted is consistent with the partial factor method adopted in the Eurocodes. To determine the values of these factors, test results from literature databases were used for calibration purposes, after a careful screening process. Regarding the temperature conversion factor, both the maximum service temperature experienced by the material and its glass transition temperature are considered; for composite materials, the method also distinguishes between fiber- and matrix-dominated properties. As for the moisture conversion factor, the proposed values consider specific exposure conditions of composite structures in service. Despite

this comprehensive effort, further experimental data is warranted to improve the reliability of the estimates of such conversion factors.

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CONFLICT OF INTEREST

The authors declare they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.