

Short- and long-term deflections of RC slabs strengthened with CFRP systems under sustained loading and different environmental conditioning

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ABSTRACT

This study investigates the combined effects of sustained loading and environmental conditioning on the short- and long-term mid-span deflection behavior of reinforced concrete (RC) slabs strengthened using different CFRP-based techniques: (i) Externally Bonded Reinforcement (EBR), (ii) Near-Surface Mounted (NSM), (iii) EBR with prestressing via mechanical anchorage (EBR-MA), and (iv) EBR with prestressing via gradient anchorage (EBR-GA). Over a period of up to six years, each of the 24 studied slabs was subjected to a sustained load equivalent to approximately 40 % of its ultimate capacity and exposed to one of the following six environmental conditions: (i, ii) two controlled laboratory settings— 20 °C and 55 % relative humidity in a climatic chamber, and full immersion in tap water at 20 °C in tanks; (iii to vi) four outdoor exposure sites across Portugal, each characterized by distinct humidity levels, temperature variations, freeze-thaw cycles, and UV radiation exposure. Instantaneous and long-term mid-span deflections were recorded and compared with the adopted predictive models. The results demonstrate that both the axial stiffness of the CFRP and the selected strengthening technique significantly influence deflection magnitude. For the instantaneous response, the Gilbert approach combined with the *fib* MC (2020) formula provided improved agreement with the measurements. Regarding long-term behavior, the Age-Adjusted Effective Modulus Method with a modified tension-stiffening model enabled derivation of slab-specific bond-dependent coefficients. Furthermore, the observed deflections closely align with the predicted values, and the proposed time-dependent factor curves (spanning up to 50 years), developed using a generalized Kelvin model together with ACI 318R-19, offer a valuable tool towards establishing simplified predictive models.

1. Introduction

Reinforced concrete (RC) is widely used in the construction of various types of structures. However, RC structures deteriorate over time due to aging, poor design, structural distress, or changes in functional requirements. In such cases, strengthening RC elements with Carbon Fiber Reinforced Polymer (CFRP) composites can significantly enhance both structural performance and durability. CFRP is often chosen over other strengthening materials because of its high strength-to-weight ratio, excellent stiffness, and resistance to harsh environmental conditions [1,2].

Externally Bonded Reinforcement (EBR) and Near-Surface Mounted (NSM) are two common techniques for strengthening RC structures with CFRP composites [3,4]. In EBR, CFRP laminates or sheets/fabrics composites are adhesively bonded to the surface of concrete, whereas NSM involves embedding CFRP laminates (or rods) into pre-cut grooves within the concrete cover [1,4]. Existing works show that strengthening

with EBR systems can increase the load carrying capacity of two-way slabs by 50 % [5], and 35 % [6] hence showcasing the effectiveness of strengthening application. Furthermore, studies have shown that the NSM can offer greater benefits compared to the EBR system [7,8]; however, it should be noted that this technique still requires further investigation, as relatively few relevant studies are currently available [7]. In some cases, active strengthening systems are required. Therefore, prestressed strengthening methods based on mechanical anchorage (MA) or gradient anchorage (GA) systems have been adopted to enhance load carrying capacity and reduce crack formation and growth, as discussed in [9–11]. In both MA and GA systems, prestressing is applied to the CFRP laminate using the structural element to be strengthened as a reaction frame. The CFRP laminate is typically bonded to the concrete substrate with epoxy adhesives, which serve as the primary load-transfer medium. In the MA system, special end-anchorage—usually metallic plate assemblies—are required to transfer the prestressing force from the CFRP laminate to the concrete and to prevent premature peeling or

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debonding failures [11]. This method ensures reliable utilization of the CFRP laminate's tensile capacity but necessitates relatively bulky hardware and precise installation to minimize stress concentrations and local damage at the anchorage zones. By contrast, the GA system achieves force transfer by gradually reducing the prestressing force in the CFRP laminate to zero over a predefined bond length [11]. In the investigated system, this is accomplished using a specialized stressing and heating device: the adhesive is cured sector-wise under controlled heating while the prestress is released stepwise from the hydraulic jack, thereby establishing a force gradient. This eliminates the need for permanent mechanical anchorages, such as steel plates, resulting in a more compact and integrated solution. However, the long-term effectiveness of GA remains highly dependent on the mechanical and durability properties of the adhesive, the quality of the concrete substrate, and the environmental exposure conditions. Further description about these MA and GA systems can be found in existing literature published by team of this work [12]. The inclusion of these two techniques is motivated by their higher potential practical advantages in improving serviceability and delaying crack growth or debonding, and increasing the ultimate capacity as compared to non-prestressed systems. In fact, previous studies, e.g., [10,13,14], have highlighted the efficiency of prestressed CFRP systems in enhancing stiffness and short-term behavior, although comprehensive evidence under sustained loading and environmental exposure is still limited.

Numerous studies have demonstrated the effectiveness of these techniques, establishing CFRP laminates as a reliable solution for improving the performance and extending the service life of RC structures under a wide range of conditions [1,15].

The long-term performance of RC structures strengthened with CFRP composites has been widely investigated through experiments on beams or slabs subjected to sustained loads for extended durations. Studies have evaluated strengthened RC elements under sustained loading for periods ranging from 200 days [16], 300 days [17], 400 days [18], two years [19], to six years [20], and beyond, to assess performance under prolonged stress conditions. These investigations have provided critical insights into the behavior of CFRP-strengthened RC members, such as the effect of increased sustained loading, duration of exposure, and environmental exposure on creep and long-term deflection developments.

Parameters such as instantaneous and long-term mid-span deflections, concrete creep coefficients, and CFRP strain evolution were addressed in previous studies, considering both sustained loading and various environmental conditioning. Key findings from selected studies are as follows: (i) the combined effect of freeze-thaw cycles and sustained loading can reduce ultimate load capacity by up to 8 % after three years [21], (ii) the concrete creep coefficient varies depending on the type of strengthening and exposure condition [22], (iii) strengthened beams exhibit lower long-term deflections compared to non-strengthened beams after nearly two years of conditioning at 19–24 °C and 30–59 % RH [18], (iv) a hot-wet environment significantly affects the durability and long-term performance of RC beams with CFRP strengthening systems [23], and both increased temperature and sustained loading contribute to higher long-term deflections [24,25], and (v) long-term deflections may reach 42–46 % of the instantaneous deflection after six months under various sustained loading levels [16].

Existing works, e.g., [18,25–29], have also proposed and/or developed analytical models to predict the long-term flexural behavior of RC structures strengthened with CFRP composites under sustained loading, addressing both prestressed and non-prestressed CFRP systems. Findings generally show that the age-adjusted effective modulus method (AEMM) is a reliable approach for predicting long-term flexural behavior of such structures. Some models incorporate the long-term behavior of CFRP using a CFRP creep coefficient, e.g., [27,30]. Additionally, the creep behavior of the adhesive layer can be accounted for by modifying the CFRP behavior using an interface creep coefficient, e.g., [25,31].

The ACI 318R-19 guideline [32] also offers a simplified method for

estimating time-dependent deflections of non-prestressed members. This approach includes the effect of a time-dependent factor and compression reinforcement ratio and has been applied to RC members strengthened with CFRP, e.g., [12,18]. Similarly, the *fib* MC (2020) [33] provides guidance on deflection prediction in RC members strengthened with CFRP using both EBR and NSM techniques. Among all contributing factors, concrete creep is widely considered the primary cause of long-term deflection. Accordingly, both the *fib* MC (2020) [33] and ACI 318R-19 [32] offer comprehensive methodologies for evaluating concrete creep effects.

While substantial knowledge exists regarding concrete creep and shrinkage, further research is required to better understand their impact on the long-term flexural performance of RC structures strengthened with CFRP systems. Particularly, limited research has been conducted on the long-term behavior of RC slabs strengthened with prestressed CFRP systems, which are also not yet addressed in existing standards, highlighting the need for further investigation. Furthermore, investigations on the effects of long-term environmental exposure periods are also needed to better understand the degradation mechanisms in the RC elements with CFRP systems. To address these gaps, the present study examined 24 RC slabs strengthened with either prestressed or non-prestressed CFRP composites under different exposure conditions. Each slab was subjected to a sustained load of approximately 40 % of its ultimate capacity and conditioned in six different environments (both indoor and outdoor). Mid-span deflections were monitored for up to six years, and analytical models based on Gilbert approach, age-adjusted effective modulus method (AEMM), *fib* MC (2020) [33], and the ACI 318R-19 [32] were developed and validated against the experimental results. A specific bond-dependent coefficient was obtained for each slab studied. Furthermore, a creep- and shrinkage-based deflection model was established to extrapolate deflection trends over a 50-year period. Using this model, the ACI 318R-19 [32] time-dependent approach was adopted to generate time-dependent factor curves, which may play a key role in the future development of generalized models, especially those accounting for complex outdoor environmental conditions.

Although some studies have examined effects of sustained loading with environmental conditioning, this work is distinct in addressing unique exposure scenarios and providing comparative insights across strengthening techniques, including ones with prestressed systems. Furthermore, the generated time-dependent factor curves and the bond-dependent coefficients make this work a new contribution to the existing literature on long-term behavior of strengthened concrete elements.

It is essential to note that this work examines CFRP-strengthening applied to initially undamaged/unstressed RC slabs prior to sustained loading. This approach intentionally isolates time-dependent material behavior and differs fundamentally from real-world applications where strengthening occurs on structures already under permanent dead loads. In such operational scenarios, pre-existing stresses induce concrete creep before strengthening, altering load-sharing mechanics between concrete and CFRP from the onset. The existing literature on this topic is limited; however, the available studies, e.g., [34,35] indicate that short-term post-cracking response, including post-yielding behavior and ultimate load capacity, is not significantly affected by the initial conditions. Moreover, this influence tends to decrease as the level of applied pre-stress increases (in the case of FRP pre-stressing systems). Therefore, the boundary conditions in the present study were deliberately modified to establish baseline performance under controlled conditions, free from pre-load complications.

2. Research methods

This study involved both experimental and analytical investigations on short- and long-term deflections of one-way RC slabs strengthened using different systems: (i) externally bonded reinforcement (EBR), (ii) near-surface mounted (NSM), (iii) EBR prestressed via mechanical anchorage (EBR-MA), and (iv) EBR prestressed via gradient anchorage

(EBR-GA). The slabs were exposed to different exposure conditions, and their midspan deflections were monitored experimentally and predicted analytically using multiple approaches, as outlined in Fig. 1. The experimental program included a description of the RC slabs, details of the conditioning types, and the procedures used to monitor deflections over a 6-year period. These methods were followed for analytical predictions: (i) instantaneous deflections were predicted using the method proposed by Gilbert [36] and a tension stiffening model from the *fib* MC (2020) [33]; and, (ii) long-term deflections were predicted using the Age-adjusted Effective Modulus Method (AEMM) coupled with a modified tension stiffening model, and the ACI 318R-19 [32] approach with the established creep and shrinkage deflection model.

2.1. Experimental program

2.1.1. Description of the slabs and sustained loading

The properties and types of the studied strengthened RC slabs are presented in Table 1, and their cross-sectional dimensions, geometries, and loading conditioning are shown in Fig. 2. To compare the amount of CFRP across different strengthening systems and study its influence on short- and long-term deflection, the equivalent axial stiffness of CFRP (K_f), calculated as CFRP elastic modulus times its total cross-sectional area, is obtained as shown in Table 1. Since K_f is directly linked with the stiffness of the strengthened RC slabs and, therefore, with the deflection, it was used as a unifying metric to compare the strengthening systems. The slab with NSM presents the smallest axial stiffness, while that of EBR presents the largest stiffness. The EBR-MA and EBR-GA systems present axial stiffness comparable to that of the slab with NSM. The four strengthening systems were intentionally designed to achieve comparable ultimate failure loads, thereby enabling a meaningful comparison of their long-term resistance to degradation and their efficiency in terms of CFRP consumption, while preserving flexibility for designers in selecting the most suitable technique.

All the slabs were cast using a single concrete batch with the following properties: a maximum aggregate size of 12.5 mm, cement type of CEM II/A-L 42.5 R, water-to-cement ratio equal to 0.4, slump ranging between 160 and 210 mm (slump class S4), exposure class XC4 (P), and concrete class of 30/37 MPa (C30/37). The concrete 28-day average compressive strength and elastic modulus obtained from tests performed on concrete cylinders of 150 mm diameter and 300 mm

height were 41.5 MPa and 29.1 GPa, respectively. The 28-day average concrete splitting tensile strength was 3.4 MPa.

The epoxy adhesive used to bond the CFRP laminate to concrete was a commercial cold-curing S&P resin 220 produced by S&P® Clever Reinforcement Ibérica Lda [38], with a flexural elastic modulus greater than 7.1 GPa, tensile strength of 19.9 MPa after seven days of curing at 20 °C and a glass transition temperature (T_g) of 46.2 °C after seven days of curing at 23 °C.

The CFRP laminates, also supplied by S&P® Clever Reinforcement Ibérica Lda [39], with a trademark of CFK 150/2000 with different cross-sections (Fig. 2a,b,c), were prefabricated by pultrusion with a unidirectional fiber orientation, 68 % fiber content, and a vinyl ester resin as the fiber matrix (with a T_g of around 85 °C). Also, according to the supplier [39], the elastic modulus and tensile strength of the laminates are greater than 170 GPa and 2000 MPa, respectively.

The steel rebars of class A400 NR SD (as per Eurocode 2 [40]) of 8 mm ($\varnothing 8$) and 6 mm ($\varnothing 6$) diameter were applied as bottom and top reinforcements, respectively; 6 mm ($\varnothing 6$) stirrups spaced at 300 mm were used as transverse rebars, as shown in Fig. 2a,b,c. It should be noted that the amount of steel reinforcement can significantly affect long-term performance of beams strengthened with FRP systems [41].

Further details about the epoxy adhesive and CFRP laminate were previously provided in [42] and those of concrete in [43]. Also, a detailed information on the production and application of the strengthening systems for the studied slabs can be found in [22,37].

It should be noted that a series of slabs, identical to those highlighted in Fig. 2, were initially tested under four-point bending to establish baseline responses and enable future comparisons of ultimate capacity after environmental exposure. The ultimate failure loads of slabs strengthened with NSM, EBR, EBR-MA, and EBR-GA systems were 62.28, 66.47, 67.62, and 59.98 kN, respectively. Each strengthened slab was designed for a target ultimate capacity of 60 kN, corresponding to approximately twice that of the reference slab. The measured failure loads therefore validated the effectiveness of the strengthening systems in achieving this predefined design objective. The failure mode was FRP rupture for the NSM and EBR-MA systems, whereas intermediate crack debonding governed the failure of the EBR and EBR-GA systems. Detailed results of these pre-exposure tests are reported in [37]. Importantly, these baseline results will serve as a critical benchmark for comparison with the post-exposure tests scheduled after 10 years,

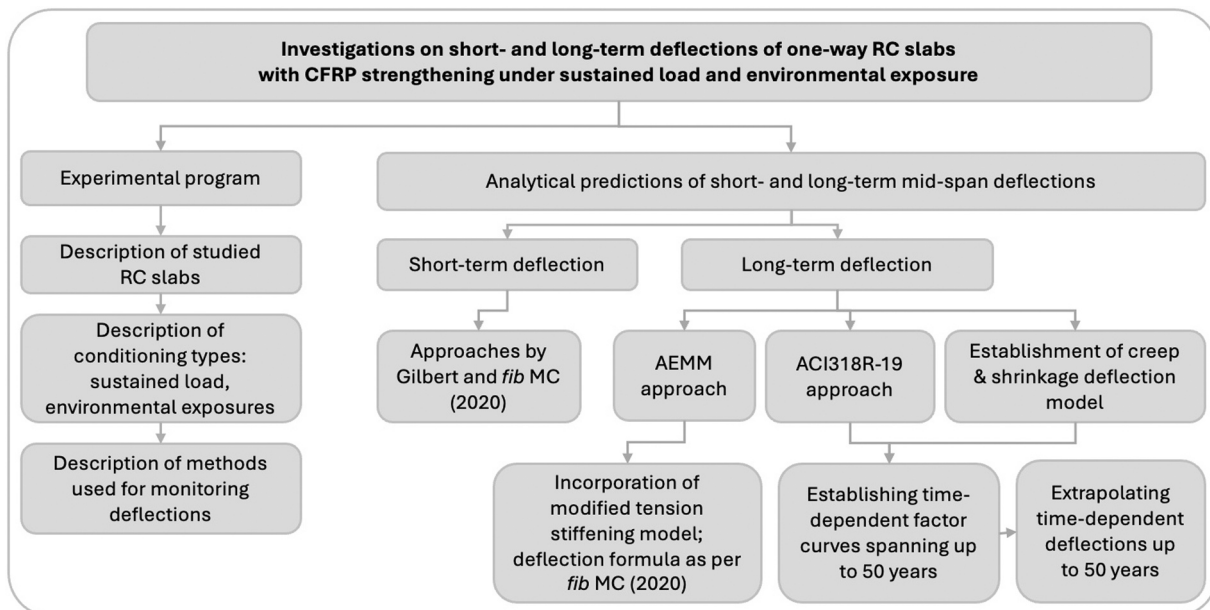


Fig. 1. Workflow on short- and long-term deflection monitoring and prediction.

Table 1

Properties of the investigated strengthened RC slabs [37].

RC Slab	CFRP laminate [mm ²]	AT	ϵ_{fp} [%]	E_s [GPa]		f_y [MPa]		f_t [MPa]		E_f [MPa]	f_f [GPa]	K_f [kN]
				$\Phi 6$	$\Phi 8$	$\Phi 6$	$\Phi 8$	$\Phi 6$	$\Phi 8$			
EBR	100 × 1.2	-	-	219.9 (1.6)	209.3 (7.7)	543.9 (1.8)	551.2 (0.8)	670.0 (0.9)	635.4 (0.5)	187.2 (0.9)	2895.2 (4.4)	22.46 × 10 ³
NSM	4 × 10 × 1.4	-	-	241.4 (5.3)	228.1 (3.2)	528.2 (0.7)	581.3 (0.6)	687.1 (0.7)	698.3 (0.3)	185.0 (1.5)	2858.2 (2.0)	10.36 × 10 ³
EBR-MA	50 × 1.2	M	0.4	219.9 (1.6)	209.3 (7.7)	543.9 (1.8)	551.2 (0.8)	670.0 (0.9)	635.4 (0.5)	184.3 (2.9)	2980.3 (4.1)	11.06 × 10 ³
EBR-GA	50 × 1.2	G										

Notes: AT: anchorage type (M - mechanical; G - gradient); values in parentheses are coefficients of variation in percent; E_s and E_f , and f_t and f_f are the elastic moduli and ultimate tensile strengths of steel and CFRP, respectively; ϵ_{fp} and f_y are initial prestrain of the CFRP and yield strength of steel, respectively; K_f is the CFRP axial stiffness.

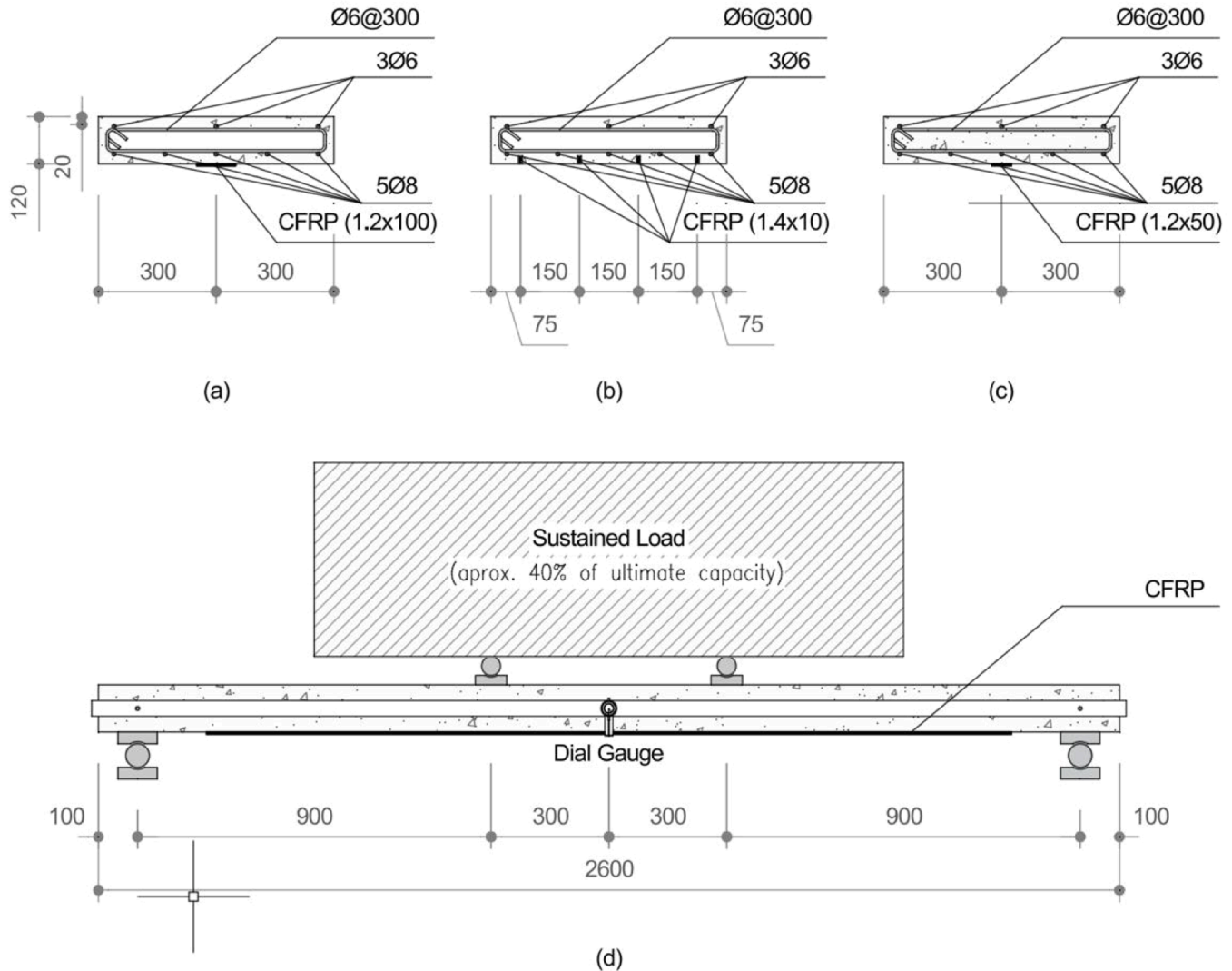


Fig. 2. Details of the slabs studied: section representing RC slab with (a) EBR, (b) NSM, and (c) EBR-MA or EBR-GA systems; (d) full RC slab representative of the slabs with sustained load applied under 4-point bending test configuration. Note: all units in [mm].

thereby allowing evaluation of the long-term effects of sustained loading and environmental conditioning on the ultimate performance of strengthened slabs.

Approximately one year after concrete casting, the remaining strengthened slabs were simultaneously loaded (each with a sustained load of 23.8 kN) using a four-point bending configuration (see Fig. 2d) and exposed to different environments. The sustained load level was fixed around 40 % of the ultimate capacity, a value within the 30–50 %

range commonly observed in RC members under service conditions as per [44]; also, commonly adopted in long-term serviceability studies of RC members, e.g., [25,27,28]. This level reflects realistic service load conditions while ensuring safety margins against ultimate failure. This conditioning aimed to investigate the combined effects of sustained loading and environmental exposure on mid-span deflection over time. Applying the sustained loading in the same four-point bending configuration provides a controlled and repeatable framework for assessing

flexural serviceability, yet it presents a limitation with respect to direct simulation of distributed service loads. However, this configuration is the most widely applied approach in long-term studies due to its simplicity, repeatability, and the technical challenges associated with maintaining distributed loads over extended periods.

2.1.2. Description of environmental conditioning and monitoring works

This study employed six different environments, comprising of two laboratory-based and four outdoor environments. The laboratory-based conditions included: (i) specimens (Fig. 3a) conditioned at 20 °C and 55 % relative humidity (E1), and (ii) specimens (Fig. 3b) fully immersed in tap water at 20 °C (E2). Mid-span deflections were monitored using a combination of LVDTs and dial gauges in E1 and E2, with readings acquired every 24 s. This setup enabled precise recording of the instantaneous and early-age deflection behavior; the comparisons of measured

deflections from the above combination were also performed.

For the outdoor environments, four regions in Portugal were selected, each representing a dominant degradation agent based on regional characteristics: (i) E3-Lisbon (Fig. 3c): mild Mediterranean climate in urban area, resulting in elevated atmospheric carbon dioxide; (ii) E4-Serra da Estrela (Fig. 3d): highest mountain in Portugal, high thermal amplitudes, lowest temperatures in Portugal, UV radiation, and freeze-thaw; (iii) E5-Elvas (Fig. 3e): warm temperature climate, very high thermal amplitudes, highest temperature in Portugal, and UV radiation; and (iv) Viana do Castelo (E6, Fig. 3f): maritime moist environment-Atlantic Ocean, with high salinity and chlorides. Although the outdoor environments were carefully selected to represent a dominant degradation agent, field exposures are inherently uncontrollable. It should be noted that the quantitative parameters from the above studied environments including the variations of temperature, humidity, and



Fig. 3. Environmental exposures: laboratory-based with (a) conditioning at 20 °C and 55 % relative humidity; (b) conditioning at 20 °C under tap water immersion; outdoor environments mainly promoting degradation due to (c) high CO₂ emissions, (d) freeze-thaw attacks, (e) high temperatures, and (f) high humidity and airborne chlorides.

carbonation can be found in a previous study by authors [45]. Environments E3 and E5 are generally characterized by higher temperatures and lower levels of humidity, whereas E4 and E6 exhibit lower temperatures and higher humidity levels. Specimens in E4 were subjected to several natural freeze–thaw cycles, providing a basis for comparison with typical accelerated ageing protocols.

UV radiation was not directly measured in this study; however, it is expected to have a less pronounced effect due to the soffit positioning of the CFRP strengthening systems, likely limiting UV exposure (except in E4 where UV effect can be more pronounced due to snow reflections, but since snowfall in Portugal does not last longer, the effect may also be assumed minimal). The outdoor sites E3–E6 were selected to capture representative degradation mechanisms relevant to Southern European climates, these conditions are aligned with typical service environments for RC structures in the region and have been shown in prior studies to significantly influence concrete and epoxy resin durability, and CFRP–concrete bond durability performance [42,46,47].

To ensure the reliability of dial gauges used in complex environments, the following measures were adopted: (i) high-quality corrosion-resistant gauges were selected; (ii) careful installation included protective enclosures and shields (Fig. 3e) to limit dust, moisture, and other effects; and (iii) measurement accuracy was verified by installing an LVDT on one side and a dial gauge on the other to record mid-span deflection; this configuration was maintained for six years in environments E1 and E2. Furthermore, the environmental stations, secured with restricted access, were also periodically inspected and maintained as needed.

It should be noted that, in addition to mid-span deflection measurements, the experimental program also included monitoring of crack development as well as the evolution of concrete and CFRP strains over time. However, these detailed results are not presented herein, as the current study is specifically focused on deflection behavior and its prediction, the latter not directly following crack propagation patterns. Given the breadth of data collected for 24 slabs across six environments, the inclusion of full crack and strain results and analysis would substantially extend the paper length and, somehow, out of the main scope of this work; therefore, these findings will be reported in forthcoming publications.

2.2. Prediction of short-term deflection

The short-term analysis of RC slab can be performed through section analysis, considering both uncracked and cracked states, from which the short-term deflection is calculated using the weighted average method proposed by *fib* MC (2020) [33]. The material constitutive models under serviceability limits are defined as follows: concrete under compressive states, reinforcing steel and CFRP laminate are considered linear elastic [48].

Referring to Fig. 4, and following the approach proposed by Gilbert [36], the neutral axis depths under uncracked (x_1) and cracked (x_2) states can be determined based on the material properties (concrete, steel, and CFRP laminate) and section geometry. These values, x_1 and x_2 , are then used to calculate the second moments of area for the uncracked (I_1) and cracked (I_2) sections, respectively. According to Gilbert [36], the short-term strain (ε_1) and curvature (k_1) for the uncracked section are calculated using Eq. (1) and Eq. (2), respectively. Similarly, the short-term strain (ε_2) and curvature (k_2) for the cracked section are obtained using Eq. (3) and Eq. (4), respectively.

$$\varepsilon_1 = \frac{B_1 M}{A_1 I_1} + \frac{I_1 N}{B_1^2} \quad (1)$$

$$k_1 = \frac{A_1 M}{A_1 I_1} + \frac{I_1 N}{B_1^2} \quad (2)$$

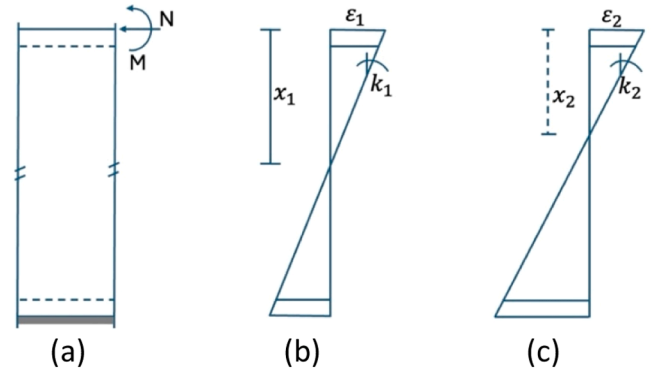


Fig. 4. (a) Section elevation, and distribution of short-term strain and curvature under (b) fully uncracked and (c) fully cracked states [36].

$$\varepsilon_2 = \frac{B_2 M}{A_2 I_1} + \frac{I_2 N}{B_2^2} \quad (3)$$

$$k_2 = \frac{A_2 M}{A_2 I_1} + \frac{I_2 N}{B_2^2} \quad (4)$$

In these equations, A_i , B_i , and I_i are the section area, first moment of area, and second moment of area, respectively; i stands for 1 or 2 indicating the uncracked or cracked section, respectively. Furthermore, M and N are the stress resultants for the cross section (axial force and bending moment) with respect to the top fiber of the cross-section [30, 36].

Following the method provided in the *fib* MC (2020) [33], deflection can be predicted using Eq. (5), where the deflections for the uncracked (δ_1) and cracked (δ_2) sections are determined using Eq. (6) and Eq. (7), respectively. The terms $[M/E_{ci}(t_0) \cdot I_1]$ and $[M/E_{ci}(t_0) \cdot I_2]$ representatives of the curvatures, k_1 and k_2 , can be calculated using Eq. (2) and Eq. (4), respectively. The interpolation coefficient (ζ) incorporating the tension stiffening effect can also be determined using Eq. (8) as per *fib* MC (2020) [33].

$$\delta_{t0} = (1 - \zeta) \cdot \delta_1 + \zeta \cdot \delta_2 \quad (5)$$

$$\delta_1 = k_M \cdot l^2 \cdot \frac{M}{E_{ci}(t_0) \cdot I_1} \quad (6)$$

$$\delta_2 = k_M \cdot l^2 \cdot \frac{M}{E_{ci}(t_0) \cdot I_2} \quad (7)$$

$$\zeta = 1 - \beta \cdot \left(\frac{M_{cr}}{M} \right)^2 \quad (8)$$

In these equations, M_{cr} is the cracking moment obtained from section analysis considering the material constitutive models (with evolved compressive strength and modulus of elasticity up to loading time determined as per Section 14.9.1 and 14.9.3 of *fib* MC (2020) [33], respectively) and the effect of CFRP strengthening and prestressing; β is a coefficient to account for influence of loading type and duration on the average strain (equal to 0.5 for sustained loads [33]); $E_{ci}(t_0)$ is the concrete modulus of elasticity at loading, estimated following the *fib* MC (2020) [33]. Furthermore, l and k_M are the span length and the coefficient depending on the load bearing system, respectively; $k_M = (1/4) - [(a/l)^2/3]$ for a four-point bending test configuration, where a is the shear span.

2.3. Prediction of long-term deflection using AEMM

The long-term analysis of RC slab can be performed using section

analysis, considering time-dependent uncracked and cracked states. From these, the time-dependent moments of area are obtained by incorporating the evolving properties of the relevant materials, namely, concrete, steel, CFRP and adhesive, along with relevant section characteristics. These moments of area are then used in the modified tension stiffening model [16] to compute the time-dependent effective moment of area. The resulting effective moment of area, combined with the effective moduli of the materials, is then used to determine the time-dependent deflection.

2.3.1. Concrete

The AEMM can be used to model the time-dependent behavior of concrete using Eq. (9), where $E_c(t, t_0)$ is the effective time-dependent concrete modulus of elasticity at time (t) , measured starting at the time of application of the sustained load (t_0) , $\varphi(t, t_0)$ and χ are the time-dependent concrete creep coefficient and aging coefficient, respectively. The χ varies between 0.7 and 0.9, and in many existing studies its value is usually taken as 0.8 for normal strength concrete, e.g., [16,24,36]. The $\varphi(t, t_0)$ can be determined experimentally by recording the long-term concrete strains under a sustained stress, if no tests performed, it can be found from existing models.

$$E_c(t, t_0) = \frac{E_{ci}(t_0)}{1 + \chi \bullet \varphi(t, t_0)} \quad (9)$$

The creep coefficient $\varphi(t, t_0)$ can be estimated referring to *fib* MC (2020) [33] as shown in Eq. (10). The terms $\varphi_{bc}(t, t_0)$ and $\varphi_{dc}(t, t_0)$ are the basic and drying creep coefficients, respectively, and further details on their determination is provided in [33,49]. The parameters ξ_{bc1} and ξ_{dc1} are equal to 1.0 if no tests on the considered concrete were carried out, otherwise, they are determined from a least square fit to the measured data. Furthermore, the code also provides thorough details on how to incorporate the effects of temperature and relative humidity variations in Eq. (10).

$$\varphi(t, t_0) = \xi_{bc1} \bullet \varphi_{bc}(t, t_0) + \xi_{dc1} \bullet \varphi_{dc}(t, t_0) \quad (10)$$

2.3.2. CFRP laminate

The time-dependent modulus of the CFRP laminate, $E_f(t, t_0)$, can be calculated using Eq. (11) [25,27], where E_f is the initial CFRP elastic modulus and $\varphi_f(t, t_0)$ is the CFRP creep coefficient, which can be determined using Eq. (12) according to [25,27].

$$E_f(t, t_0) = \frac{E_f}{1 + \varphi_f(t, t_0)} \quad (11)$$

$$\varphi_f(t, t_0) = 0.02 \bullet (1 - e^{\frac{-(t-t_0)}{130}}) \quad (12)$$

2.3.3. Interface behavior

The time-dependent deformation occurred at the CFRP-to-concrete interface (throughout the adhesive) can be considered by introducing an interface creep coefficient, $\varphi_a(t, t_0)$, defined in Eq. (13) as proposed in [31] and adopted in [25], which in turn can be incorporated in the model as an additional creep coefficient of the CFRP laminate [25], leading to the total time-dependent effective modulus of the CFRP as Eq. (14) [25]. Specifically, the interface behavior is incorporated in the time-dependent age-adjusted effective modulus of the CFRP via Eq. (14), which builds on the CFRP modulus, $E_f(t, t_0)$, previously updated in Eq. (11) using its time-dependent creep coefficient. Therefore, the resulting effective modulus in Eq. (14) reflects the combined contribution of both the CFRP and the interface creep coefficients.

$$\varphi_a(t, t_0) = 1.65 \bullet (1 - e^{\frac{-(t-t_0)}{160}}) \quad (13)$$

$$E_{fa}(t, t_0) = \frac{E_f(t, t_0)}{1 + \varphi_a(t, t_0)} \quad (14)$$

Eq. (13) describes long-term interface behavior under standard laboratory conditions and does not explicitly include all environmental effects. This equation incorporates the time-dependent response of the bond through the interface creep coefficient. Unlike concrete, whose creep is significant and well-characterized with environmental effects incorporated in standard formulations, the creep of the interface is not yet standardized or well-defined, and available models do not explicitly account for all environmental variations. Moreover, the CFRP and interface are minimally affected by creep compared to concrete, thus leading to insignificant contributions on the overall deflection trends [33]; hence, making Eq. (13) appropriate for capturing the dominant time-dependent response, despite the omission of environmental effects (these effects can phenomenologically be represented when selecting the bond dependent coefficient as will be discussed in Section 2.3.4).

2.3.4. Section analysis

With the time-dependent material properties defined in Sections 2.3.1 to 2.3.3, a section analysis accounting for time-dependent effects can be performed. The application of Eq. (9) to Eq. (14) leads to modification of the transformed section properties by updating the modular ratios of the bottom steel reinforcement [$\alpha_{s1}(t, t_0) = E_{s1}/E_c(t, t_0)$], top steel reinforcement [$\alpha_{s2}(t, t_0) = E_{s2}/E_c(t, t_0)$] and CFRP laminate [$\alpha_f(t, t_0) = E_{fa}(t, t_0)/E_c(t, t_0)$]. It should be noted that the neutral axis depth should ideally be updated at each time step, as it depends on the time-dependent modular ratios. However, for simplification, the neutral axis position can be assumed constant over time, which has been shown to yield to acceptable accuracy in previous studies, e.g., [25,36].

Referring to Fig. 5, the time-dependent effective second moment of area $I_e(t, t_0)$ can be determined following the modified tension stiffening model [16,30], as defined in Eq. (15). This calculation incorporates the time-dependent uncracked [$I_1(t, t_0)$] and cracked [$I_2(t, t_0)$] second moments of area, both of which are updated based on the time-dependent modular ratios. The values $I_1(t, t_0)$ and $I_2(t, t_0)$ are determined referring to the curvatures $k_{e1}(t, t_0)$ and $k_{e2}(t, t_0)$ respectively, as shown in Fig. 5. Here, k_1 and k_2 are as previously defined, while k_{e1} and k_{e2} represent the time-dependent curvatures in the uncracked and cracked states, respectively.

Knowing the $I_e(t, t_0)$ and $E_c(t, t_0)$, the time-dependent curvature term [$k_e(t, t_0) = M/E_c(t, t_0) \bullet I_e(t, t_0)$] can be calculated and used to determine the total mid-span deflection [$\delta_e(t, t_0)$] accounting for both the instantaneous and time-dependent components, using Eq. (16) as per to *fib* MC (2020) [33].

$$I_e(t, t_0) = \left(\frac{M_{cr}}{M}\right)^3 \cdot \beta_d \cdot I_1(t, t_0) + \left[1 - \left(\frac{M_{cr}}{M}\right)^3\right] \cdot I_2(t, t_0) \leq I_1(t, t_0) \quad (15)$$

$$\delta_e(t, t_0) = k_M \cdot l^2 \cdot \frac{M}{E_c(t, t_0) \cdot I_e(t, t_0)} \quad (16)$$

where $\beta_d = \alpha_b \cdot (E_f/E_s + 1)$; α_b is a bond dependent coefficient, and E_f/E_s is the ratio of CFRP to steel modulus of elasticity. It should be noted that Eq. (16) does not account for the pre-existing condition of the slab, as is typically the case in real applications where strengthening systems are installed on members already subjected to bending moments, cracks, and deflections induced by existing loads. For such scenarios, the formulations provided in Section 30.8.63 of the *fib* MC (2020) [33] are more appropriate and should be used instead of Eq. (16).

2.4. Prediction of long-term deflection using ACI 318R-19

ACI 318R-19 standard [32] has provided a simplified expression in Eq. (17) for predicting the creep and shrinkage-based deflection (λ_Δ) for non-prestressed members.

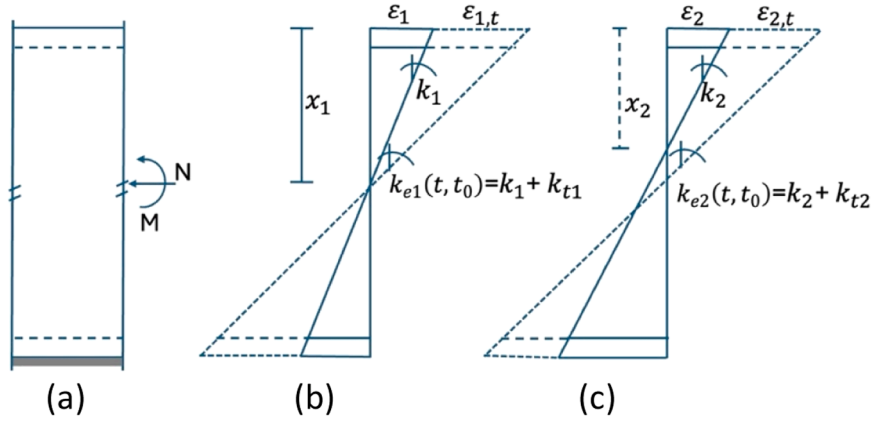


Fig. 5. (a) Section elevation, and distribution of time-dependent strain and curvature under (b) fully uncracked and (c) fully cracked states.

$$\lambda_{\Delta} = \delta_{t0} \cdot \left(\frac{\xi}{1 + 50\rho'} \right) \quad (17)$$

The terms δ_{t0} , ξ , and ρ' are the instantaneous deflection, time-dependent factor for sustained load, and the compression reinforcement ratio, respectively. The term ξ varies with time for up to five years, thereafter, becoming constant. It should be noted that this assumption of a plateau provides a practical design simplification; existing works [33, 50] have indicated that creep may continue to evolve beyond this timeframe, highlighting the need for further long-term data to refine such models.

For RC flexural members strengthened with CFRP systems, the effect of strengthening is not explicitly considered in Eq. (17). However, since the long-term deflection is primarily governed by the concrete compression zone [33], the application of ACI 318R-19 remains valid even for strengthened members as the stresses at the CFRP-concrete interface are typically low under service loads, contributing minimally to creep development [33]. Several existing studies have also applied Eq. (17) to RC members strengthened with CFRP systems, e.g., [12,18].

2.5. Creep deflection model

The AEMM approach introduced in Section 2.3 relies heavily on the modified tension stiffening model [16], particularly on the bond-dependent coefficient, which has not yet been accurately calibrated for different strengthening systems. This is especially true for prestressed CFRP systems, which are currently not addressed in existing standards. Additionally, the ACI 318R-19 provision presented in Section 2.4 has been shown to significantly overpredict long-term deflections, as noted in several studies, e.g., [18,50].

In outdoor environments, complex degradation mechanisms, including synergistic effects that are not accounted for in current standards and guidelines, make the development of accurate predictive models particularly challenging. Even when such models are developed, they are often computationally intensive and difficult to implement in design practice [33]. For this reason, the formula in the ACI 318R-19 standard remains valuable for design purposes due to its simplified nature. It can be used to derive time-dependent factor curves that define the long-term behavior of RC members under various strengthening systems and conditioning types. In doing so, it indirectly incorporates the complex environmental effects. These time-dependent factor curves can be extended to longer durations using robust viscoelastic models such as the Generalized Kelvin (GK) chain model, assuming that long-term deflections are primarily governed by the viscoelastic behavior of concrete, which is consistent with established guidelines [1, 32].

The GK model is schematically presented in Fig. 6 and can be expressed as a Dirichlet series in Eq. (18) [51], where E_0 represents the

initial elastic response, $E_{i(i=1,\dots,N)}$ represents the elastic component of each element, and $\eta_{i(i=1,\dots,N)}$ represents the viscous component, where N is the number of GK chains considered. In this formulation, D_0 and D_i are comparable to E_0 and E_i , respectively, since the long-term deflection-time curve is primarily governed by the viscoelastic behavior of concrete [1,33]. A creep deflection model based on the GK model can be developed by minimizing the error function in Eq. (19) using optimization tools (e.g., MATLAB's Optimization Toolbox) or machine learning. The optimized parameters can then be applied in Eq. (20) to estimate deflection over time.

$$D(t) = D_0 + \sum_{i=0}^n D_i (1 - e^{-t/(\tau_i D_i)}) \quad (18)$$

$$f = \sum_{j=1}^m (D(t) - \mathfrak{D}(t))^2 \quad (19)$$

$$D_C(t) = \sum_{i=0}^n D_i (1 - e^{-t/(\tau_i D_i)}) \quad (20)$$

Where, $D(t)$ is the total long-term deflection at time t , n is the number of Kelvin chains, τ_i , D_i and D_0 are the coefficients of Dirichlet series; f is the objective function, m is the number of points employed during optimization process, $\mathfrak{D}(t)$ is the experimentally recorded deflection, $D_C(t)$ is the creep deflection function.

2.6. Prediction of deflection for the studied slabs

The method presented in Section 2.2 was adopted to predict the instantaneous deflection. For the time-dependent deflection prediction, described in Section 2.3, values of the temperatures and relative humidity, previously published by the authors in [43,45], were used to model the concrete creep coefficient, accounting for the effects of the environmental conditions investigated. That is, the used average peak temperatures and average relative humidities for E3, E4, E5, and E6 were 42.2 °C and 71.93 % RH, 30.65 °C and 69.63 % RH, 42.98 °C and 65.12 % RH, and 35.15 °C and 77.55 % RH, respectively. These values are based on data spanning up to four years due to sensor malfunctions in outdoor environments; however, given the consistent trends observed, the four-year averages can be considered representative of longer-term conditions. The bond-dependent coefficient α_b is a key parameter reflecting the combined influence of material creep, loading condition and environmental effects. The coefficient β_d , used in the long-term stiffness formulation, depends on α_b and the elastic moduli of CFRP and steel reinforcement as shown in Section 2.3.4. While literature generally adopts a value of 0.5 for all FRP systems [30], β_d should theoretically be updated at each time step to account for evolving

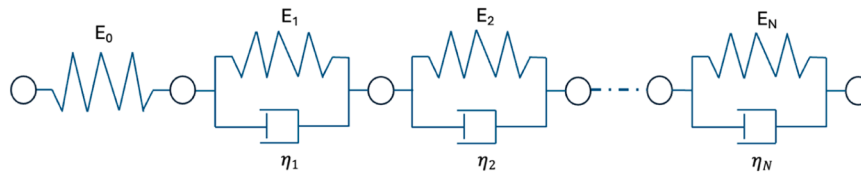


Fig. 6. Idealized schematic representation of Generalized Kelvin chain model (adapted from [51]).

material moduli. Such updates would require detailed knowledge of complex, largely uncontrollable phenomena resulting from loading and environmental conditions used in this work. Hence, a characteristic α_b was instead determined via parametric calibration, incrementally varied using a small step size (0.001) until the predicted long-term deflections showed good agreement with experimental observations. Since the material moduli were kept constant, α_b indirectly captured the cumulative effects of time-dependent changes. This approach allows accurate reproduction of long-term slab behavior without explicitly tracking complex environmental and material interactions over six years. It should be recalled that both CFRP and interface creep coefficients were assumed to remain unaffected by the type of environmental exposure. This assumption was made due to the current lack of literature quantifying how different environmental conditions might alter these coefficients. Indeed, the complexity of outdoor environments, where multiple factors interact in uncontrolled and often synergistic ways, makes isolating such effects highly challenging. Hence, the effects of exposure conditions on the interface behavior were phenomenologically incorporated while calibrating the bond dependent coefficient. While this assumption can provide a reasonable basis for the present work, it also highlights a gap in knowledge that future research could address—particularly through controlled simulations of coupled environmental conditions, which would enable more accurate parameterization of these coefficients. The effects of updating the neutral axis location or incorporating the interface model on the calibrated bond dependent coefficients were also assessed via sensitivity and statistical analyses.

The ACI 318R-19 method, introduced in Section 2.4, was applied to all tested slab types to evaluate its capability in predicting creep- and shrinkage-based deflection.

The approach outlined in Section 2.5 was used to establish time-dependent factor curves governing each investigated strengthening system under all conditioning types. These curves were further used to extrapolate deflections up to 50 years. To minimize the error function defined in Eq. (19), several optimization algorithms from the MATLAB toolbox were tested. Among all, the gradient-based *fmincon* with constrained optimization technique was found to be the most accurate and consistent across all studied environmental conditions and was therefore selected to identify the optimal parameters. To determine the optimal number of chains, two to ten chains were tested, and four chains were selected as they provided the best agreement with experimental deflection histories while maintaining computational efficiency. The obtained fitting parameters were assumed to represent the viscoelastic behavior of concrete, given its dominant creep deformation, compared to other slabs' constituent materials, as previously discussed in Section 2.5. However, these parameters should be interpreted as *phenomenological* fitting parameters representing the *combined* creep contributions of concrete, CFRP, and the interface, rather than direct material properties. In fact, the term “*phenomenological*” is used to explain that although concrete creep is well described by viscoelastic chains, the long-term behavior of CFRP and the CFRP–concrete interface can involve additional mechanisms such as polymer relaxation, bond micro-slip, and degradation. Hence, all these effects can be thought incorporated *phenomenologically* within the GK framework, enabling accurate reproduction of the overall time-dependent deflection response without explicitly modelling each mechanism. The impact of shrinkage was considered negligible as loading was applied one year after casting. As a

result, shrinkage-induced deflection over time (t) was obtained from a simplified shrinkage exponential model $\delta_{sh} = e_{sh,max}(1 - \exp(-k_{sh}\sqrt{t}))$ [33], scaled by the instantaneous deflection, where a maximum shrinkage strain $e_{sh,max} = 0.002$ and shrinkage coefficient $k_{sh} = 1e-5$ were used. This shrinkage deflection model was added to the creep deflection model (Section 2.5) to obtain the total fitting model curve, but its effect on the fitting curve was very minor, highlighting insignificant effect of shrinkage. This shrinkage model was assumed applicable to all studied environments and was mainly introduced to help perform comparisons with the ACI 318R-19 standard [32] which addresses both creep and shrinkage effects.

3. Results and discussion

3.1. Experimental short- and long-term deflections

The mid-span deflections obtained from experimental monitoring of the slabs in each of the studied environments are presented in Fig. 7. Furthermore, the comparison of LVDTs and dial gauges in the indoor setup (Fig. 8) shows identical deflection records even after long-term monitoring, confirming the reliability and accuracy of the dial gauges used in the outdoor environments. Creep in concrete under sustained load is conventionally described by three stages [50]: an initial stage of decreasing creep rate, a secondary stage of nearly constant creep rate, and a tertiary stage of accelerated deformation leading to failure. In the present study, the recorded data clearly demonstrates the occurrence of primary and secondary creep stages, after the initial instantaneous response. However, the precise onset of secondary creep (i.e., the termination of primary creep) cannot be distinctly identified, due to variability in long-term slab behavior influenced by temperature and relative humidity, as well as the inherent ambiguity in defining the concept of a nearly constant deformation rate among other aspects. Slabs strengthened with the NSM system exhibited the largest instantaneous deflection, attributed to the smaller CFRP axial stiffness used (approximately 40 % less compared to that of the EBR system, presenting nearly two-fold). In contrast, slabs strengthened with prestressed systems (EBR-MA and EBR-GA) exhibited approximately 30 % lower instantaneous deflections compared to the non-prestressed EBR system. These slabs also showed total deflections below 16 mm in all environments after six years. This improved performance is primarily attributed to the prestressing action, which helps oppose both dead and applied loads [52].

For the slabs subjected to laboratory-based conditioning (E1 and E2), the deflections were notably smaller than those recorded under outdoor conditions, as shown in Fig. 7. Under E1, deflections gradually increased over time, reaching approximately 15 mm (EBR), 20 mm (NSM), and 12 mm (EBR-MA and EBR-GA) after six years. In contrast, under E2, deflection increases were negligible. The greater deflection observed under E1 is likely due to moisture exchange with the environment and the presence of air, which may have exacerbated creep deformation. The limited deflection in E2 can be attributed to: (i) restricted moisture migration due to full submersion in water, (ii) minimal thermal stresses due to stabilized temperature, and (iii) absence of drying shrinkage-induced deflection, since the concrete remained fully saturated.

Slabs exposed to outdoor environments generally exhibited higher time-dependent deflections, particularly in regions with high

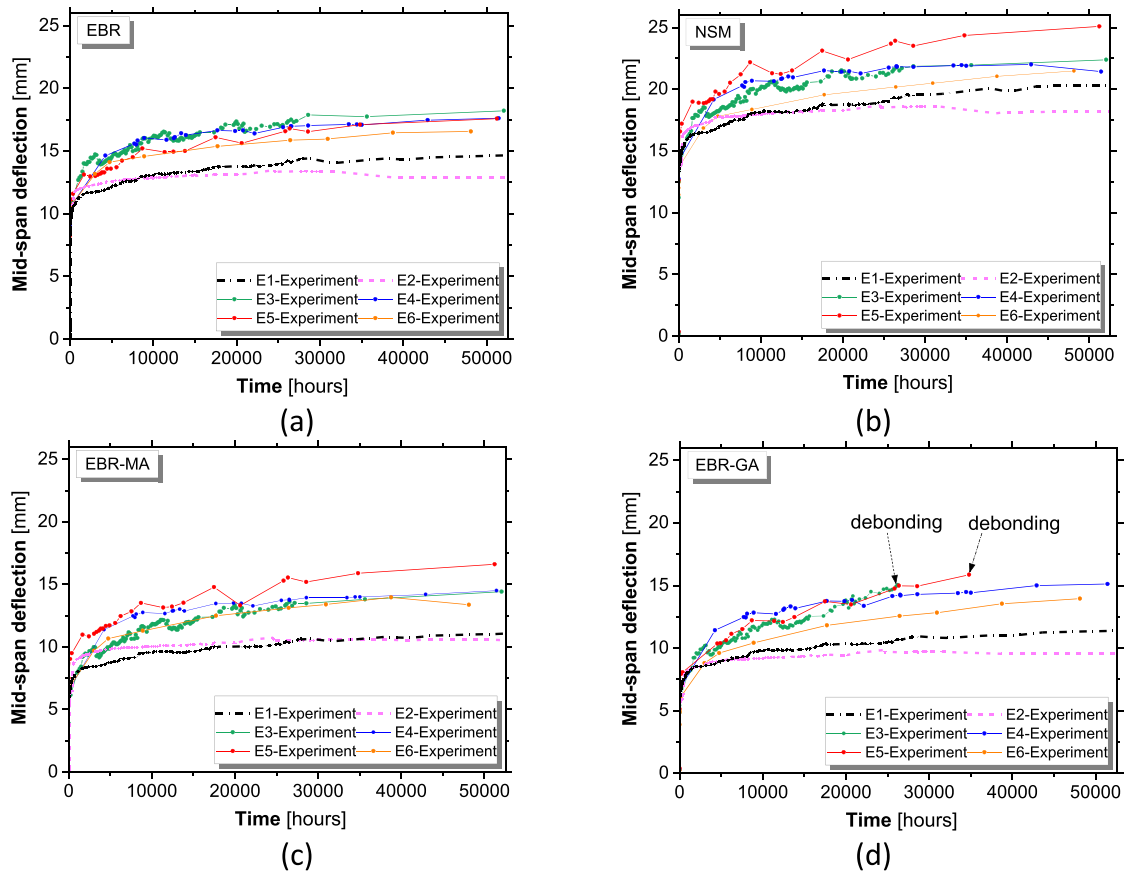


Fig. 7. Experimentally monitored mid-span deflection of slabs strengthened with (a) EBR, (b) NSM, (c) EBR-MA, and (d) EBR-GA systems over a period of up to six years (50,000 h).

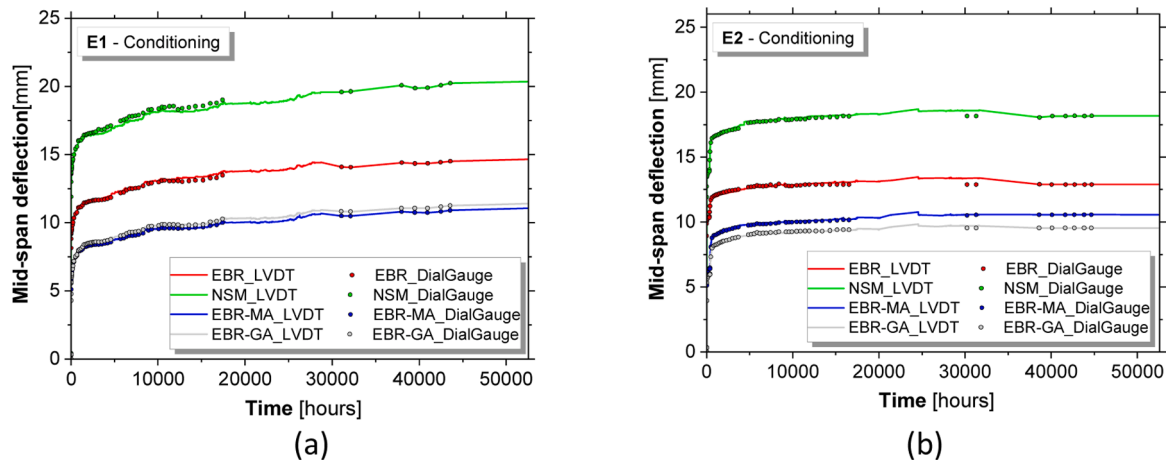


Fig. 8. Comparison of mid-span deflection measurements obtained using LVDT and dial gauge for CFRP-strengthened slabs under (a) E1 and (b) E2 conditioning over a period of up to six years (50,000 h).

temperatures (E5). The combined effect of elevated CO_2 concentrations and high temperatures (E3) might have also led to the observed increased deflection. Similarly, the degradation agents in E4 might have led to the observed greater deflections compared to those in E6. After six years, the measured long-term deflection ranges were as follows: (i) slabs with EBR: 16–18 mm; (ii) slabs with NSM: 21–25 mm; (iii) slabs with EBR-MA: 13–16 mm; and (iv) slabs with EBR-GA: 14–16 mm.

The instantaneous and total deflections, along with their percentage difference (used to interpret the contribution of creep and shrinkage on the long-term deflection), are presented in Table 2. Regardless of

environmental exposure, the prestressing systems (EBR-MA and EBR-GA) increased the proportion of creep and shrinkage-based deflection compared to the non-prestressed EBR system).

The maximum values of the deflections due to creep and shrinkage effects were observed in E3 and E5, with approximately 174 and 175 % increases when compared with the instantaneous deflections, respectively. These findings indicate that regions characterized by higher temperatures (E5) and those with elevated CO_2 levels combined with high temperatures (E3) exhibit greater creep and shrinkage effects in prestressed systems compared to the other regions studied. Interestingly,

Table 2
Comparison of instantaneous and total deflections after six years.

Environmental conditioning	EBR	NSM	EBR-MA	EBR-GA
E1	8.13 / 14.77 (81.7)	14.15 / 20.42 (44.3)	5.10 / 11.17 (119)	4.77 / 11.50 (141.1)
E2	8.94 / 12.89 (44.2)	13.48 / 18.17 (34.8)	5.82 / 10.56 (81.4)	5.33 / 9.55 (79.2)
E3	8.84 / 18.21 (106.0)	13.90 / 22.37 (60.9)	5.26 / 14.41 (174.0)	4.82 / 15.05*
E4	9.08 / 17.61 (93.9)	14.08 / 21.42 (52.1)	5.33 / 14.50 (172.1)	5.79 / 15.11 (161.0)
E5	8.21 / 17.58 (114.1)	14.07 / 25.09 (78.3)	6.04 / 16.60 (174.8)	5.14 / 15.87**
E6	8.92 / 17.58 (97.1)	12.45 / 21.47 (72.5)	5.36 / 13.37 (149.4)	4.69 / 13.94 (197.2)

Notes: Instantaneous deflection (δ_{i0}) versus deflection after six years (δ_{6Y}), data presented as δ_{i0}/δ_{6Y} and their percentage difference is shown in parentheses to represent the creep & shrinkage-based deflection); * and ** are the values recorded at two and four years, respectively.



Fig. 9. Monitoring of time-dependent responses in CFRP-strengthened slabs: concrete cohesive-dominated failure modes observed in (a) E3 and (b) E5; (c) soffit of slab with EBR-GA system in E4 after six years of exposure; crack widths (in mm) measured for NSM slab after (d) one, (e) two, and (f) six years of exposure in E3; and (g) deflected shape of the EBR-GA system in E5 after six years of exposure.

the slab with the non-prestressed EBR system exhibited lower deflection increases in E3 (106 %) and E5 (114 %), although still higher than those in other environments. This contrast highlights that the applied prestress in EBR-MA and EBR-GA systems significantly contributed to the observed increase in long-term deflections. This phenomenon can be explained by the increased concrete compression zone resulting from prestressing. As concrete creep is primarily governed by the compression zone [1,33], the added compressive zone led to greater long-term deformation. As a result, the prestressed systems experienced deflection increases of approximately 68 % (E3) and 61 % (E5) relative to the non-prestressed case, attributable pertinently to the effect of enhanced compression.

Notably, in E3 and E5, the debonding failures of EBR-GA slabs (see Fig. 9a,b) were observed as concrete cohesive failures, with localized regions of deeper detachment in E5 exposing parts of the tension steel reinforcement (see Fig. 9b). Following debonding, a sudden increase in deflections was recorded, rising from 15.05 mm to 25.26 mm in E3 and from 14.95 mm to 27.90 mm in E5. This behavior underscores the fundamental role of the applied prestress in mitigating the effects of sustained loading by limiting curvature and bending moments. Once the prestress effect was lost, the balance between external load and internal resistance was altered, leading to a rapid increase in curvature and, consequently, a pronounced growth in slab deflections. No direct microscopic or mechanical property testing could be performed on the debonded parts within the present phase of the study due to (i) the CFRP laminates did not fully detach from the slabs; hence, making it unfavorable to remove it and do these testing, and (ii) such analyses are planned as part of the ongoing 10-year monitoring program, together with load-to-failure tests, to provide a more comprehensive mechanistic understanding. Contrary, the slab with the same EBR-GA system in E4 is still unaffected visually as no debonding has occurred yet even after six years of exposure (Fig. 9c), hence, highlighting the different effects from environmental exposures.

The observed failures in E3 and E5 can be attributed to several interacting mechanisms. First, the epoxy adhesive curing under prestress in the EBR-GA system has been shown to lead to significant reductions of mechanical properties, due to increased pore formation during high-temperature curing [9]; this can weaken the adhesive matrix, promoting crack initiation and premature debonding [9], which can be inferred to have occurred in the studied slabs. Secondly, according to a study in [53], the epoxy adhesive used may experience a 30–40 % reduction in its mechanical properties. Additionally, exposure to temperatures approaching the adhesive's glass transition temperature can further compromise bond performance. Both factors may have contributed to the observed premature debonding. Lastly, adhesive softening, thermal expansion mismatches, and reduced mechanical properties under prolonged high temperatures may have further compromised the bond, ultimately resulting in debonding failure.

Referring to the existing works [9,53] and the observations from the present work, the failure mechanism in the EBR-GA slabs can be interpreted in two stages. *Stage 1* involves adhesive weakening during the gradient anchorage process due to heating-induced porosity, as reported in [9], combined with the stress redistribution introduced by the sustained load applied after prestressing. At this stage, all slabs with EBR-GA systems, regardless of environment, share the same condition of reduced bond performance. *Stage 2* distinguishes the environmental effects: in E3, carbonation combined with high temperatures accelerate degradation of the adhesive-concrete interface, while in E5, elevated temperatures exacerbate the loss of adhesive capacity. These combined effects triggered debonding in E3 and E5, whereas EBR-GA slabs in other environments (e.g., E4 shown in Fig. 9c) did not experience failure under similar sustained loads, underscoring the decisive role of environmental conditions.

However, it should be noted that due to inherent nature of outdoor exposures, in the above explained stage 2, for the case of E3, elevated CO₂ levels likely acted in concert with other outdoor degradation agents

to promote carbonation- and high temperature-induced microstructural changes, stiffness reduction, and bond deterioration at the CFRP-concrete interface; in E5, higher temperatures and thermal cycling variability plausibly accelerated creep in concrete and the polymer matrix and amplified differential hygro-thermal strains and interfacial slip. Hence, due to synergistic interactions occurred in the studied environments, the final outcome does not allow apportioning the contribution of individual drivers.

In contrast to the higher deflections seen in E3 and E5, the slabs in E6 exhibited the lowest long-term deflections among the prestressed systems (EBR-MA and EBR-GA). This reduced deflection can be attributed to the high humidity of the environment, which helps retain internal moisture within the concrete and reduces drying creep. As a result, shrinkage-related stresses are minimized, and total creep deformation is limited.

It should be noted that the durability performance of the investigated slabs' constituent materials (concrete, adhesive, and CFRP) and EBR/NSM CFRP-to-concrete bond behavior at small-scale levels have been previously reported in [42,43,45,46], from which the key findings are provided herein: Concrete compressive strength and elastic modulus increased notably in outdoor environments (E3–E6), with maximum rises of 21 %, 16 %, 21 %, and 17 % for strength, and 9 %, 12 %, 3 %, and 12 % for modulus, while laboratory environments (E1, E2) showed only marginal changes. Concrete pull-off strength decreased progressively in all environments. The adhesives experienced substantial reductions under water immersion during the first years (≈ 66 % in tensile strength and 75 % in elastic modulus), with minimal post-curing in other environments. CFRP laminates initially improved in tensile strength (15–16 %) and elastic modulus (≈ 10 %) due to post-curing, followed by gradual decreases, yet remained above the values of unexposed specimens even after four years. EBR CFRP-to-concrete bond performance in tested small-scale specimens, representative of full-scale slabs, was strongly influenced by time and environmental exposure. Bond stiffness degraded faster than bond strength in most environments, with the largest reductions observed in E4 (50 %), E2 (40 %), E5 (39 %), and E3 (35 %), and smaller reductions in E1 and E6. Bond strength generally decreased over time in laboratory environments (E1 and E2), tended to increase with fluctuations in outdoor environments (E3 and E4), and remained largely stable in E5 and E6. Elevated temperatures (E5) caused a pronounced 39 % reduction in stiffness while bond strength remained essentially unchanged. NSM CFRP-to-concrete bond performance also varied with time and environment. The largest reductions in bond strength occurred under continuous water immersion (E2, -12 %) and freeze–thaw exposure (E4, -9 %), while bond strength increased in laboratory (E1, $+10$ %) and outdoor environments (E5 and E6), likely due to beneficial effects of temperature, carbonation, airborne chlorides, and changes in concrete properties. Environmental effects from E3 had minimal impact. Bond stiffness initially decreased across all environments but generally increased in subsequent years, particularly in laboratory-controlled conditions.

Although the materials and bond performance in small-scale specimens under different investigated environments is known, their long-term behavior in slabs may differ from that observed in isolated tests. In fact, in the above previous works, the material properties did not reflect the same degradation trends as the bond due to interface interactions and because their testing was performed on specimens (size, shape) not fully representative of the bonded region. Most importantly, although placed in the same environments, the exposure conditions for materials were different from those of the bond (e.g., the CFRP and epoxy adhesives were directly exposed to the UV and rain, while epoxy and CFRP in the bond were not directly exposed to these degradation agents). Likewise, the bond in full-scale slabs may behave differently from small-scale materials and NSM/EBR CFRP-to-concrete bond specimens (without any sustained load effects), as sustained loading during exposure can alter stress distributions and induce time-dependent changes, and additionally, due to different exposure conditions as

explained above. Therefore, while material and small-scale bond tests provide valuable insights, the bond behavior in slabs under sustained load and environmental exposure cannot necessarily be assumed to mirror trends seen in isolated specimens.

Representative crack patterns after one, two, and six years of exposure for a representative slab strengthened with NSM in E3 environment are presented in Fig. 9d,e,f. Although no detailed crack analysis is provided, as this lies beyond the scope of the present study, the substantial increase in crack widths over time is evident and corroborates the observed long-term trends in deflection growth. Furthermore, visual deflection shape of a selected slab after a prolonged period of sustained loading and environmental exposure is provided in Fig. 9g. The apparent deformation, characterized by visible sagging, offers qualitative evidence of significant long-term deflection. This observed behavior aligns with and provides visual corroboration for the quantitative deflection trends measured instrumentally and presented in this study.

The magnitude of deflection quantified in this study deviates from that previously reported in [19,20] mainly because in [19] the sustained load was not applied on the studied beams, and different loading schemes were used in [20]. These discrepancies are also attributable to several factors: (i) variations in the applied prestress level, which governs initial stiffness and time-dependent creep response; (ii) differences in environmental exposure conditions, including temperature, relative humidity, and concentrations of CO₂ or ultraviolet radiation, which significantly influence long-term material properties; and (iii) variations in structural geometry, CFRP material type, and bonding methodology, all of which alter composite interaction and stress transfer mechanisms, thereby affecting deflection evolution. This analysis underscores that the long-term serviceability performance of prestressed CFRP systems is highly sensitive to specific design parameters and environmental conditions, providing critical context for the deviations observed relative to prior research.

3.2. Predicted short-term deflection

The predicted instantaneous deflections were compared with the corresponding experimental measurements, as presented in Table 3. The maximum percentage differences observed in environments E1, E2, E3, E4, E5, and E6 were approximately 14 %, 14 %, 13 %, 7 %, 17 %, and 20 %, respectively.

These discrepancies are likely attributable to minor differences in sustained loading levels compared to those used in the predictive model. Despite these variations, the observed percentage differences can still be considered relatively small, confirming the reliability and applicability of the adopted prediction approach.

Table 3
Comparison of experimental and predicted instantaneous deflection.

Environmental conditioning	EBR	NSM	EBR-MA	EBR-GA
E1	8.13 / 8.45 (+3.9)	14.15 / 15.01 (+6.1)	5.10 / 5.00 (-2.0)	4.77 / 5.44 (+14.1)
E2	8.94 / 8.45 (-5.5)	13.48 / 15.01 (+11.4)	5.82 / 5.00 (-14.1)	5.33 / 5.44 (+2.1)
E3	8.84 / 8.45 (-4.4)	13.90 / 15.01 (+8.0)	5.26 / 5.00 (4.9)	4.82 / 5.44 (+12.9)
E4	9.08 / 8.45 (-6.9)	14.08 / 15.01 (+6.6)	5.33 / 5.00 (-6.2)	5.79 / 5.44 (-2.1)
E5	8.21 / 8.45 (+2.9)	14.07 / 15.01 (+6.7)	6.04 / 5.00 (-17.2)	5.14 / 5.44 (+5.8)
E6	8.92 / 8.45 (-5.3)	12.45 / 15.01 (+20.6)	5.36 / 5.00 (-6.7)	4.96 / 5.44 (+9.7)

Notes: Experimental ($\delta_{t0 (EXP)}$) versus predicted ($\delta_{t0 (Pred)}$) instantaneous deflections, data presented as $\delta_{t0 (EXP)} / \delta_{t0 (Pred)}$ and their percentage difference as shown in parentheses.

3.3. Predicted total deflection using AEMM

The predicted total mid-span deflections are presented in Fig. 10, alongside the corresponding experimental results. For the EBR system (Fig. 10a), the predicted deflection curves in E2 and E5 display some deviations in trend compared to the experimental data. Nevertheless, the predictions still show reasonable agreement. For the NSM system (Fig. 10b), similar discrepancies in trend are observed under E2 and E6, although the predicted values remain in good agreement with the experimental results overall.

Very good agreement is observed for the prestressed CFRP strengthening systems. In the case of the EBR-MA system (Fig. 10c), the predicted curve in E2 closely matches the experimentally recorded deflection trend, and predictions under other environmental conditions also show excellent correspondence. For the EBR-GA system (Fig. 10d), minor trend differences are noted under E2 and E6, though the overall agreement with experimental results remains good.

The bond-dependent coefficients and concrete creep coefficients used in the analysis are listed in Table 4. The former generally converges toward the value of 0.5, as recommended for all FRP reinforcements [30], with the exception of the EBR system, which showed slightly higher values. Furthermore, higher creep coefficients were observed in high-temperature regions as expected, in alignment with the *fib* MC (2020) [33].

The effect of considering the shift of neutral axis and interface model is highlighted in Fig. 11. It is observed that, at a fixed bond dependent coefficient (Table 4), omitting the shift of neutral axis over time presents insignificant effects when compared with omitting the interface model (Fig. 11a). This is confirmed for all slabs by plotting the normalized deflection considering both the neutral axis (NA) and interface behavior effects, as can be seen in Fig. 11b. The statistical analysis reveals that accurately modelling the interface behavior is fundamentally more critical than capturing neutral axis variation for predicting long-term deflections in strengthened concrete slabs. The comprehensive comparison across 22 tested slabs demonstrates that omitting interface modelling introduced substantially greater errors (RMSE: 0.990 mm, 16.0 % of deflection range; MAE: 0.975 mm, 15.8 %) compared to neglecting neutral axis variation (RMSE: 0.137 mm, 2.2 %; MAE: 0.131 mm, 2.1 %). These differences were statistically significant ($p < 0.0001$ for both RMSE and MAE), indicating that interface behavior contributes approximately seven times more to deflection accuracy than neutral axis effects. The obtained consistently high R^2 values (>0.99 across all models) confirm that all approaches capture the overall deflection trends, but the substantial differences in error metrics highlight the crucial importance of proper interface modelling for precise long-term deflection prediction. This is in line with the findings in [17] where the adhesive behavior was observed to play a major role in controlling the magnitude of deflection. This finding has significant

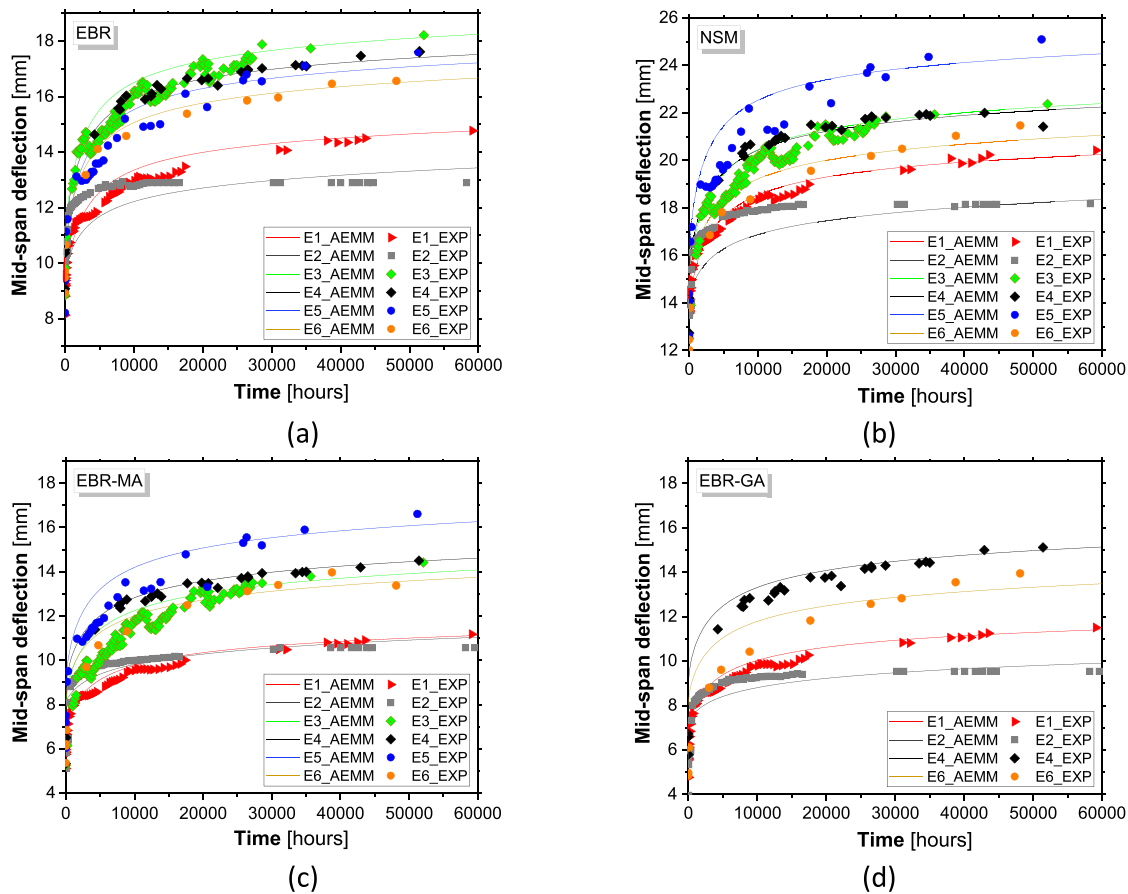


Fig. 10. Experimental monitored deflections versus analytically predicted deflections for the slabs with (a) EBR, (b) NSM, (c) EBR-MA, and (d) EBR-GA systems for up to six years. Note: Due to debonding occurred for the EBR-GA in E3 and E5, the corresponding results were not predicted.

Table 4

Bond dependent and maximum concrete creep coefficients.

Environmental conditioning	EBR	NSM	EBR-MA	EBR-GA
E1	0.83 / 1.09	0.56 / 1.09	0.56 / 1.09	0.54 / 1.09
E2	0.70 / 0.47	0.48 / 0.47	0.42 / 0.47	0.48 / 0.47
E3	0.62 / 1.24	0.49 / 1.24	0.44 / 1.24	-
E4	0.61 / 1.06	0.45 / 1.06	0.40 / 1.06	0.38 / 1.06
E5	0.72 / 1.40	0.43 / 1.40	0.40 / 1.40	-
E6	0.65 / 1.00	0.48 / 1.00	0.42 / 1.00	0.42 / 1.00

Notes: Data are presented as: bond dependent coefficient (α_b) / maximum creep coefficient (φ_u)

implications for practical design, suggesting that computational efforts should prioritize accurate interface characterization over refined neutral axis modelling when predicting serviceability performance under sustained loading and environmental exposure.

Overall, the AEMM approach demonstrated strong agreement with the experimental results across all systems and environments. Thus, this method is recommended for future studies, especially for gaining insights into the variability of the bond-dependent coefficient (α_b) and for further calibration efforts, to extend its applicability across a wider range of strengthening systems and environmental conditions.

3.4. Predicted long-term deflection using ACI 318R-19

The results obtained using the ACI 318R-19 approach are presented in Table 5, together with the experimentally recorded deflections at five and six years, as well as the percentage differences between predicted and measured values. Significant overpredictions of approximately

71 % (EBR), 320 % (NSM), 57 % (EBR-MA), and 32 % (EBR-GA), compared to the experimental results, are observed in E1 after 5 years. Overpredictions are also noted across other environments. The largest overpredictions are consistently observed for slabs strengthened with the NSM system, while the smallest discrepancies are generally recorded for prestressed CFRP systems. The larger deviation observed for the NSM system compared to EBR, EBR-MA, and EBR-GA slabs arises from its distinct bond-transfer mechanism. NSM reinforcement, being embedded in grooves, provides higher bond efficiency and reduced slip, which enhances stiffness under sustained loading. The ACI 318R-19 method, calibrated for conventional RC members, does not account for this mechanism, whereas the bond behavior of EBR and prestressed EBR systems can be thought to be more consistent with its assumptions, leading to smaller deviations. These findings suggest that the direct application of the ACI 318R-19 standard can be misleading for predicting long-term deflection in CFRP-strengthened RC slabs. Similar conclusions have also been drawn in previous studies (e.g., [18,50]).

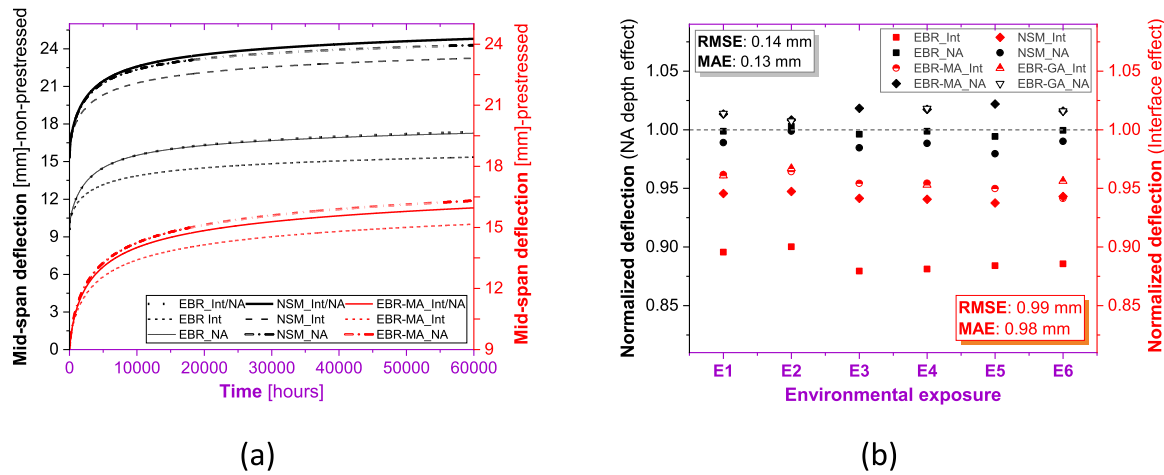


Fig. 11. Comparisons of mid-span predicted deflection considering the variability of neutral axis location over time and when omitting/incorporating interface model for (a) a selected E5 environment (with highest variations), and (b) for all studied slabs and all environments. Notes: NA stands for the case when neutral axis is assumed constant over time, while Int stands for the case when interface model is not incorporated, Int/NA stands for the case when both the shift of neutral axis over time and interface model are incorporated.

Table 5

Comparison of 5- and 6-year experimental and ACI 318R-19 predicted creep and shrinkage-based deflection.

Environmental conditioning		EBR	NSM	EBR-MA	EBR-GA
E1	δ_{5Y}	6.31 / 12.20	5.91 / 26.36	5.74 / 9.50	6.4 / 8.89
	δ_{6Y}	6.52 / 12.20	6.27 / 26.36	6.07 / 9.50	6.73 / 8.89
		(87.1)	(320.4)	(56.5)	(32.1)
E2	δ_{5Y}	3.95 / 16.65	4.68 / 25.11	4.89 / 10.84	3.92 / 10.47
	δ_{6Y}	3.95 / 16.65	4.69 / 25.11	4.74 / 10.84	3.93 / 10.47
		(321.5)	(435.4)	(128.7)	(166.4)
E3	δ_{5Y}	8.99 / 16.47	10.81 / 25.89	10.24 / 7.27	12.59 / 8.98
	δ_{6Y}	9.08 / 16.47	10.90 / 25.89	10.52 / 7.27	13.66 / 8.98
		(81.4)	(137.5)	(30.9)	(34.3)
E4	δ_{5Y}	8.35 / 16.91	9.13 / 26.23	8.96 / 9.92	9.09 / 10.79
	δ_{6Y}	8.54 / 16.91	9.15 / 26.23	9.14 / 9.92	9.36 / 10.79
		(98.0)	(186.7)	(8.5)	(15.3)
E5	δ_{5Y}	9.17 / 15.29	12.14 / 26.21	10.26 / 11.24	11.93 / 9.57
	δ_{6Y}	9.42 / 15.29	12.54 / 26.21	10.67 / 11.24	12.95 / 9.57
		(62.3)	(109.0)	(5.3)	(26.1)
E6	δ_{5Y}	7.57 / 16.61	9.80 / 23.20	8.28 / 9.98	9.84 / 7.22
	δ_{6Y}	7.79 / 16.61	10.17 / 23.20	8.38 / 9.98	10.22 / 7.22
		(113.2)	(128.1)	(19.1)	(68.5)

Notes: δ_{5Y} and δ_{6Y} are creep and shrinkage-based deflection obtained after five and six years of exposure, respectively; data are presented as: experimental value/predicted value using ACI 318R-19 approach; the values in parentheses indicate the percentage difference between experimental and ACI 318R-19 prediction after six years.

Additionally, the recorded results show that the ACI 318R-19 deflection limit at five years may be insufficient, as deflection measurements continued to increase through year six.

To reconcile the above discrepancies, time-dependent factor curves relevant to the studied slabs were derived and are presented in Fig. 12, along with the standard ACI 318R-19 curve.

Regardless of the conditioning type, the ACI 318R-19 curve deviates significantly from those derived for the tested slabs. Furthermore, the derived factors for slabs strengthened using EBR and NSM techniques are lower than those for slabs with EBR-MA and EBR-GA systems. Overall, the use of the ACI 318R-19 time-dependent factor leads to inaccurate predictions for the studied cases. Therefore, modification of this factor is recommended to account for the influence of strengthening system and environmental conditioning.

3.5. Deflection from creep and shrinkage effects

The results from the long-term monitoring, along with the fitting curves obtained from the creep and shrinkage-based deflection model,

are illustrated in Fig. 13.

The results indicate that prestressed systems exhibit higher time-dependent deflections compared to the non-prestressed systems; also, the slabs with NSM show the highest time-dependent deflections (except E2), which may be linked to the smaller CFRP axial stiffness as previously explained.

The proposed model successfully replicates the long-term deflection trends observed experimentally. The corresponding fitted parameters are provided in Table A.1 in the appendix, along with the projected 50-year total deflections. These parameters vary with strengthening and conditioning type, reflecting the distinct viscoelastic responses associated with each exposure condition. The model exhibited exceptional fidelity across all scenarios, with coefficients of determination (R^2) ranging from 0.95 to 0.99; this indicates that the model captures a minimum of 95 % of the variance in long-term deflection. The absolute error metrics were consistently minimal. The root mean square error (RMSE) ranged from 0.08 mm to 0.55 mm, with a worst-case value representing a mere 2.2 % of the maximum recorded deflection (25.09 mm). The mean absolute error (MAE) remained between

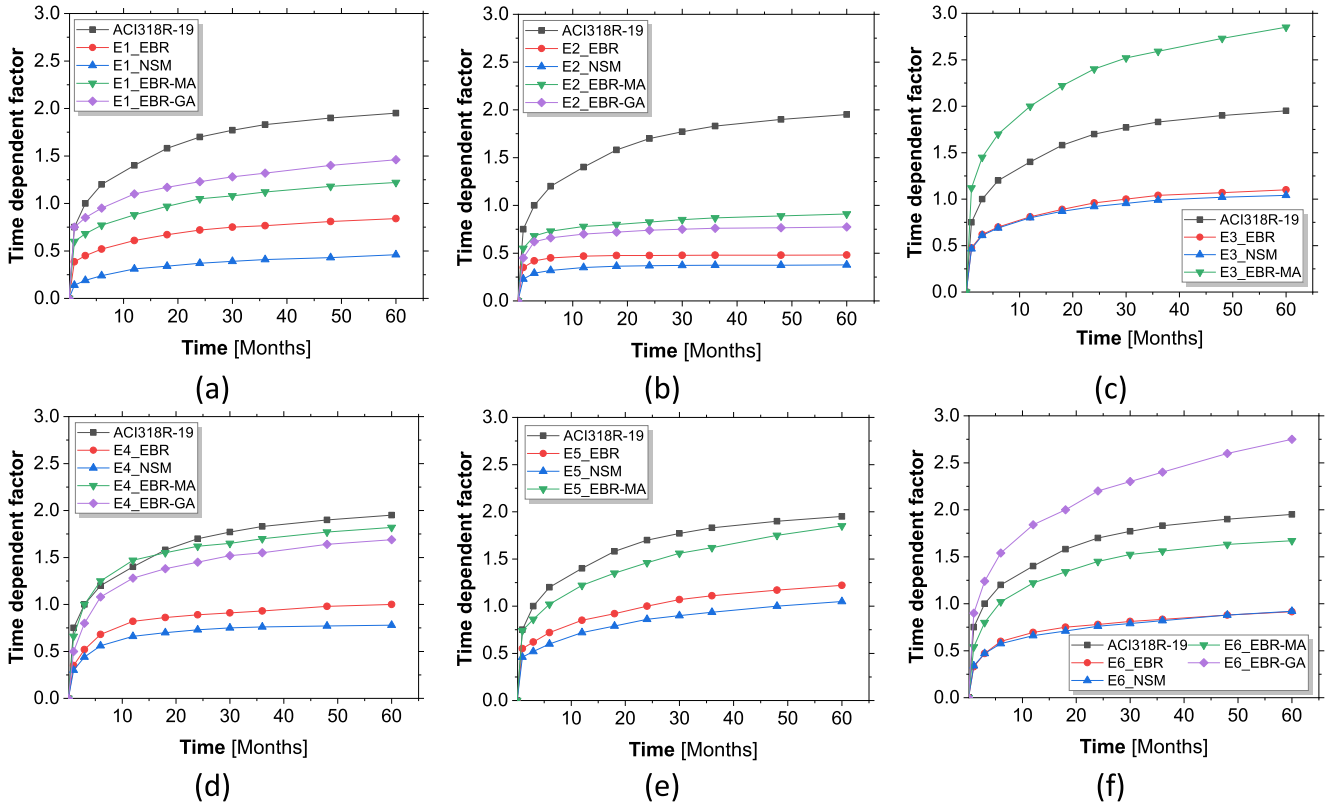


Fig. 12. Time-dependent factor curves for the slabs under (a) E1, (b) E2, (c) E3, (d) E4, (e) E5, and (f) E6 conditioning.

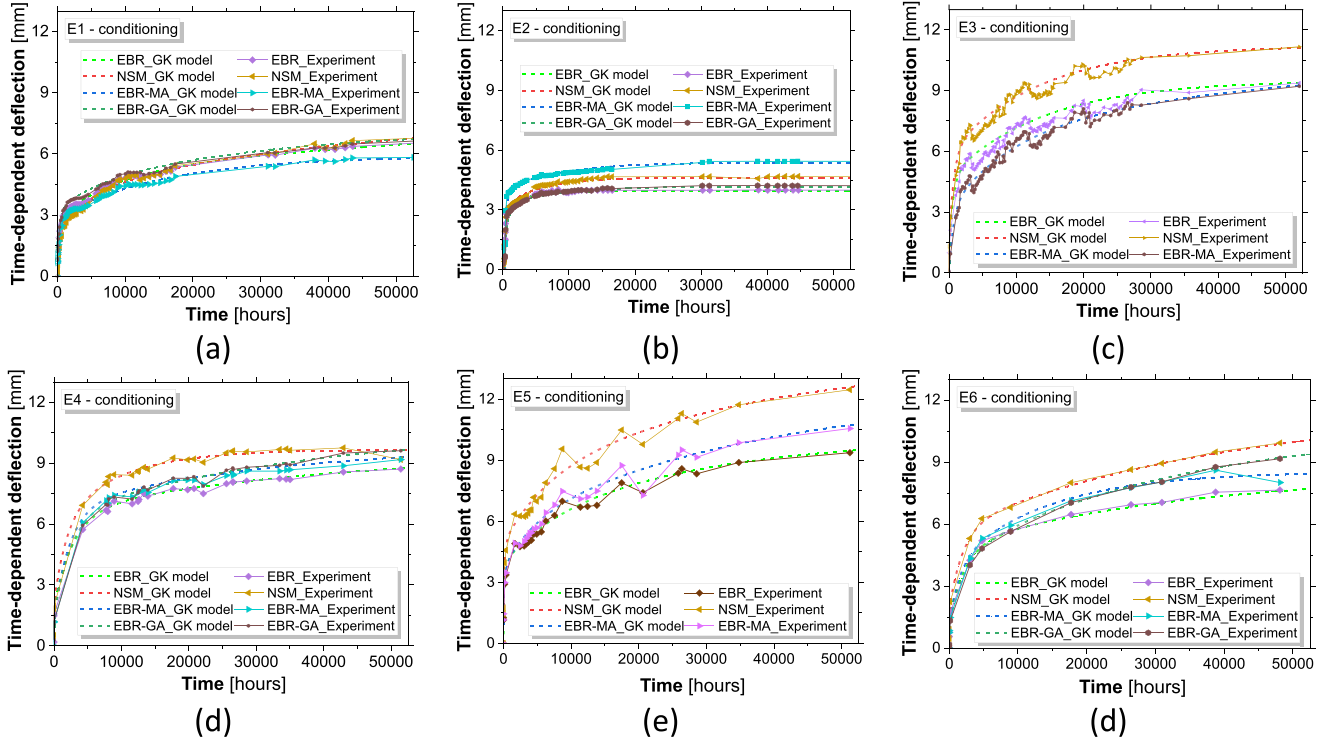


Fig. 13. Creep and shrinkage-based deflections for the slabs under: (a) E1, (b) E2, (c) E3, (d) E4, (e) E5, and (f) E6 conditioning.

0.06 mm and 0.40 mm. The narrow spread and low magnitude of these error values, coupled with the high R^2 , confirm the model's robustness and its high reliability for predicting the long-term serviceability of CFRP-strengthened slabs under different exposure conditions.

3.6. Long-term deflection prediction up to 50 years

Utilizing the ACI 318R-19 formula in combination with the established creep and shrinkage-based deflection model, the time-dependent

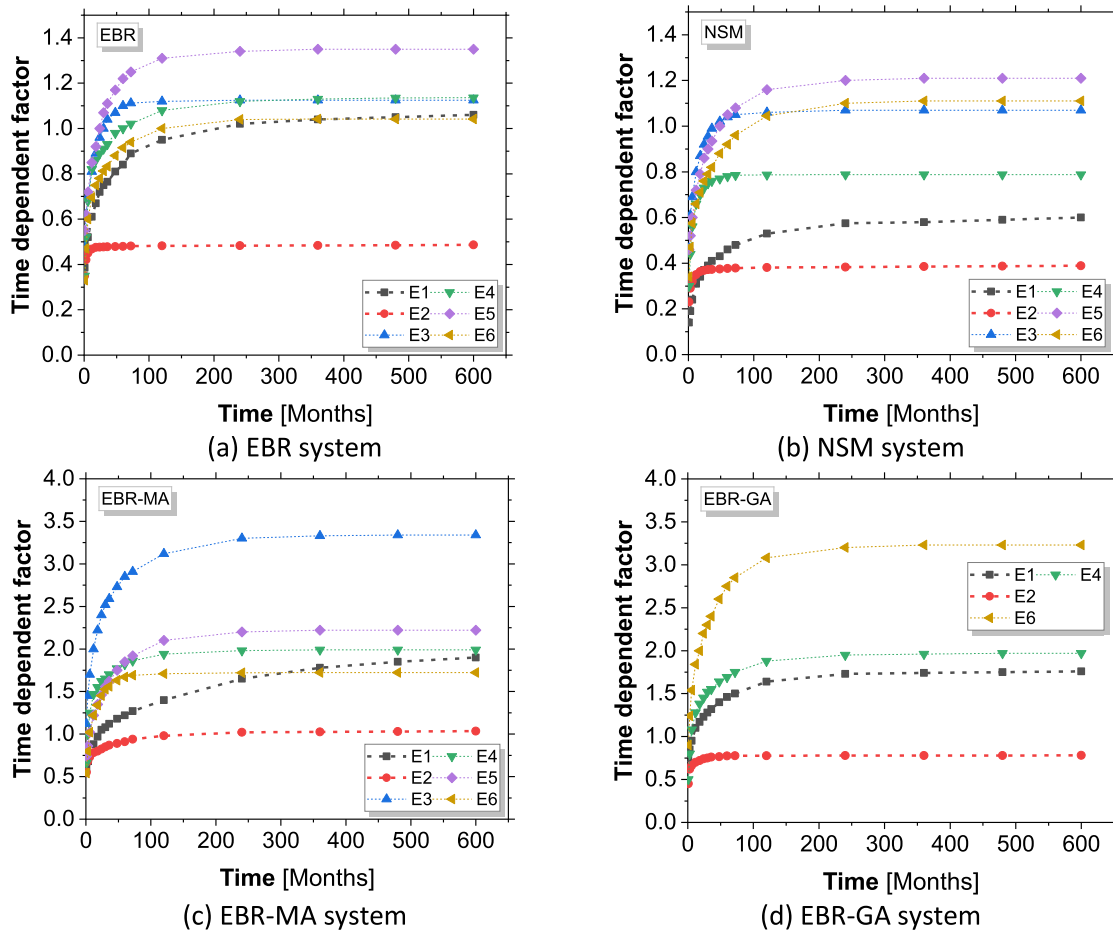


Fig. 14. Time-dependent factor curves for up to 50 years for slabs with (a) EBR, (b) NSM, (c) EBR-MA, and (d) EBR-GA strengthening systems.

factor curves originally presented in Fig. 12 were extrapolated and are now shown in Fig. 14 for each strengthening system. These extended curves may serve as a basis for deriving generalized time-dependent factors applicable to a broad range of CFRP strengthening techniques and environmental conditioning regimes.

The curves in Fig. 14 were used to estimate deflections up to 50 years, as shown in Fig. A.1 to Fig. A.4 in the appendix. In these figures, the time at which each factor curve reaches a plateau is denoted as PS (Plateau Start), allowing for a direct comparison with the ACI 318R-19 assumption. The deflection at PS is furthermore compared with the total deflection at 50 years, as presented in Table 6. For the EBR slab, the time-dependent factor peaks at 60 months for E2 and E3, with a

deflection difference of less than 0.1 % between PS and 50 years. In E1, the peak occurs around 240 months with a 2 % difference. For E4, E5, and E6, the difference is under 0.5 %. In the NSM slab, the factor peaks at 240 months for E1, E5, and E6, and at 60 months for E2, E3, and E4. For prestressed CFRP systems, the EBR-MA systems reach the peak at 480 months in E1, 240 months in E2, E3, E4, and E5, and 60 months in E6. EBR-GA systems reach the peak at 60 months in E2 and 240 months in E1, E4, and E6. Overall, in many cases the PS is found at 240 months with an acceptable percentage difference.

As previously discussed, the parameters of the GK model were calibrated using the 6-year experimental dataset. While this model can provide a solid basis for predicting material's viscoelastic behavior over

Table 6

Comparison of deflection at plateau start (PS) time with deflection at 50 years.

Environmental conditioning	EBR	NSM	EBR-MA	EBR-GA
E1	7.66 / 7.82 (2.08)	7.48 / 7.64 (2.13)	8.71 / 8.90 (2.18)	7.59 / 7.67 (1.05)
E2	3.96 / 3.96 (0.00)	4.68 / 4.68 (0.00)	5.39 / 5.41 (0.37)	3.92 / 3.92 (0.00)
E3	9.19 / 9.20 (0.10)	10.90 / 11.01 (1.00)	11.88 / 12.00 (1.01)	-
E4	9.35 / 9.39 (0.42)	9.13 / 9.17 (0.43)	9.77 / 9.78 (0.10)	10.42 / 10.46 (0.24)
E5	10.1 / 10.11 (0.09)	13.96 / 14.01 (0.35)	12.23 / 12.28 (0.41)	-
E6	8.54 / 8.56 (0.23)	11.67 / 11.74 (0.59)	8.38 / 8.48 (1.19)	11.48 / 11.51 (0.26)

Notes: Creep and shrinkage-based deflection, data presented as: extrapolated deflection at the assumed plateau start (PS) time / extrapolated deflection at 50 years; and their percentage difference shown in parentheses.

a long-term performance, the extrapolation of deflections to 50 years has not been experimentally validated and can only be reliable if the rate of change in material and interface behavior remains consistent with that observed during the initial six years. Extrapolating deflections to 50 years relies on assumed long-term evolution of material properties and bond characteristics, in a similar way as that experienced during the first six years. For epoxy adhesives and CFRP, nonlinear degradation mechanisms, such as adhesive embrittlement, fiber–matrix debonding, or creep acceleration, or synergistic effects under further increased times (in terms of decades) of sustained load, temperature, and other environmental exposures, can lead to increased or even different materials' nonlinearity trends other than those in the first six years (captured by the GK model). These trends may be characterized by fitting parameters different from those in Table A.1, thereby leading to deflection trends that deviate from those predicted using the above parameters. Consequently, due to this uncertainty, the extrapolated deflections presented herein should be interpreted as indicative trends rather than precise predictions. Further experimental studies, long-term monitoring, or advanced durability models would be required to capture these effects accurately. Therefore, the present 50-year projections serve to illustrate the potential long-term behavior of the strengthened system and to highlight the sensitivity of deflection to material property evolution, rather than to provide definitive service-life predictions.

4. Conclusions and recommendations

This study comprehensively investigated the short- and long-term deflections of 24 RC slabs strengthened using four different CFRP systems (EBR, NSM, EBR-MA, and EBR-GA) under sustained loading and subjected to six different conditioning regimes, including both controlled laboratory (E1, E2) and outdoor environments (E3–E6). The key findings are as follows:

1. Instantaneous deflection is found to be highly influenced by the CFRP axial stiffness and applied prestress, with prestressed systems (EBR-MA and EBR-GA) showing lower deflection thanks to delayed cracking and enhanced load opposition. Doubling the stiffness decreased the deflection by approximately 40 %, and 0.4 % of prestress led to approximately 30 % reduction of the deflection.
2. Long-term deflection under indoor conditions revealed minimal increase in fully immersed slabs (E2), while slabs in ambient lab air (E1) showed significantly higher deflections. The absence of moisture migration, negligible thermal stresses, and elimination of drying creep are linked to minimal deflection increase in E2, despite the known degradation of adhesive properties in wet environments. In contrast, higher long-term deflections in E1 are due to air circulation and moisture exchange, which amplified creep effects.
3. Outdoor exposure (E3–E5) led to increased long-term deflections compared to indoor exposure, inferred to be mainly linked to deterioration of adhesive properties due largely to elevated temperatures (E5) and/or increased carbonation (E3). Similarly, the slabs in regions with freeze-thaw attacks (E4) also showed moderate deflection increase. In contrast, the slabs in maritime environment (E6) showed limited deflection growth. Prestressed systems exhibited greater long-term deflections compared to non-prestressed counterparts, likely due to increased compression zone effects.
4. Analytical approach using the Gilbert [36] model combined with *fib* MC (2020) tension stiffening model accurately predicted instantaneous deflections of all slabs. The long-term predictions using the Age-Adjusted Effective Modulus Method (AEMM) coupled with the modified tension stiffening model also proved reliable; however, this approach significantly relies on a bond-dependent coefficient that needs further refinement. Conversely, the ACI 318R-19 approach consistently overpredicted deflections and failed to capture the deflection due to creep and shrinkage effects.
5. Owing to its simplicity for design practice, the ACI 318R-19 approach was used in conjunction with the Generalized Kelvin chain-based creep deflection model to establish new time-dependent factor curves tailored to different strengthening and conditioning scenarios, hence capturing the complexity of any studied exposure conditions. These curves enabled deflection extrapolation up to 50 years and revealed that, in many cases, deflection tends to stabilize after approximately 20 years. These extrapolated deflections should be regarded as indicative trends rather than precise or definitive service-life predictions, since the rate of nonlinear degradation mechanisms (e.g., adhesive embrittlement, fiber–matrix debonding, creep acceleration) or potential synergistic effects, beyond that occurred in the first six years may alter material behavior and fitting parameters, thereby leading to higher or lower deflections than predicted. These projections mainly illustrate the potential long-term response and the sensitivity of deflections to material property evolution, underscoring the need for further experimental long-term monitoring or accelerated aging studies and advanced durability models for reliable service-life assessment.
6. The error analysis demonstrated that assuming a constant neutral axis (NA) over time does not introduce significant errors in the model, hence varying NA depth over time would increase computational cost with insignificant benefits. However, omitting the incorporation of interface model can slightly alter long-term deflection predictions determined at a calibrated bond dependent coefficient, this underscores the role of considering interface behavior when modelling deflection using the AEMM approach coupled with the modified tension stiffening model.
7. While outdoor environments were selected based on dominant degradation agents, their complex and uncontrolled nature implies the presence of synergistic mechanisms. Therefore, although targeted agents likely played influential roles, no exclusive causal attribution was made.
8. While the findings from this work provide valuable insights into CFRP-strengthened RC slab behavior under controlled conditions, their direct translation to real-world structures requires significant qualification. Unlike operational scenarios (where strengthening occurs on beams/slabs with existing stress histories, crack patterns, and ongoing creep deformations), the monitored specimens represent idealized, undamaged systems strengthened prior to loading. Consequently, field applications may exhibit higher: (i) accelerated interfacial debonding due to stress concentrations at pre-existing cracks, (ii) asymmetric load redistribution favoring the CFRP system, and (iii) increased long-term deflections as per literature. These differences underscore the need for future research incorporating pre-load sequences to validate design methodologies under service-realistic conditions.

Future research on long-term deflection behavior should focus on extending the use of the AEMM coupled with the modified tension stiffening model to refine the bond-dependent coefficient, thereby enabling its broader applicability across any strengthening techniques and exposure conditions. Additionally, given the practical simplicity of the ACI 318R-19 approach, subsequent studies are encouraged to develop generalized time-dependent factor curves derived from this approach, with the aim of standardizing them for inclusion in future design codes.

Nomenclature

A_1	Area of fully uncracked transformed slab section
A_2	Area of fully cracked transformed slab section
B_1	First moment of fully uncracked transformed area
B_2	First moment of fully cracked transformed area
D_0, τ_i, D_i	Coefficients of Dirichlet series
$D_C(t)$	Creep deflection function

$\mathfrak{D}(t)$	Experimentally recorded total deflection (for fitting model)	$\varphi_a(t, t_0)$	Interface creep coefficient at time t starting at loading time t_0
$D(t)$	Total deflection (for fitting model)	$\varphi(t, t_0)$	Concrete creep coefficient at time t starting at loading time t_0
E_f	Initial CFRP modulus of elasticity	$\varphi_f(t, t_0)$	CFRP creep coefficient at time t starting at loading time t_0
E_s	Modulus of elasticity of tensile steel rebars	$\varphi_{bc}(t, t_0)$	Concrete basic creep coefficient at time t starting at loading time t_0
$E_{ci}(t_0)$	Concrete modulus of elasticity at loading time (t_0)	$\varphi_{dc}(t, t_0)$	Concrete drying creep coefficient at time t starting at loading time t_0
$E_c(t, t_0)$	Effective concrete modulus of elasticity at time t starting at loading time t_0	ξ_{bc1}	Multiplication factor for concrete basic creep coefficient
$E_f(t, t_0)$	Effective modulus of elasticity of CFRP at time t starting at loading time t_0	ξ_{dc1}	Multiplication factor for concrete drying creep coefficient
$E_{fa}(t, t_0)$	Effective modulus of elasticity of CFRP considering contribution from interface at time t starting at loading time t_0	χ	Concrete aging coefficient
f	Objective function	ρ'	Compression reinforcement ratio
I_1	Second moment of fully uncracked transformed area	x_1	Distance from top compressive fiber to the neutral axis under fully uncracked state
I_2	Second moment of fully cracked transformed area	x_2	Distance from top compressive fiber to the neutral axis under fully cracked state
$I_1(t, t_0)$	Second moment of fully uncracked transformed area at time t starting at loading time t_0		
$I_2(t, t_0)$	Second moment of fully cracked transformed area at time t starting at loading time t_0		
$I_e(t, t_0)$	Total effective second moment of area at time t starting at loading time t_0		
l	Span length		
M	Applied bending moment		
M_{cr}	Cracking moment		
N	Applied axial force		
a	Shear span		
α_b	Bond dependent coefficient		
$\alpha_{s1}(t, t_0)$	Modular ratio of bottom steel rebars at time t starting at loading time t_0		
$\alpha_{s2}(t, t_0)$	Modular ratio of top steel rebars at time t starting at loading time t_0		
$\alpha_f(t, t_0)$	Modular ratio of CFRP laminate at time t starting at loading time t_0		
β_d	Reduction coefficient		
ε_1	Concrete top fiber strain under fully uncracked state at loading time t_0		
ε_2	Concrete top fiber strain under fully cracked state at loading time t_0		
$\varepsilon_1(t, t_0)$	Concrete top fiber strain under fully uncracked state at time t starting at loading time t_0		
$\varepsilon_2(t, t_0)$	Concrete top fiber strain under fully cracked state at time t starting at loading time t_0		
k_1	Fully uncracked section curvature at loading time t_0		
k_2	Fully cracked section curvature at loading time t_0		
$k_{e1}(t, t_0)$	Fully uncracked section curvature at time t starting at loading time t_0		
$k_{e2}(t, t_0)$	Fully cracked section curvature at time t starting at loading time t_0		
k_M	Load bearing system coefficient		
δ_{t0}	Instantaneous deflection at loading time t_0		
δ_1	Instantaneous deflection under fully uncracked state at loading time t_0		
δ_2	Instantaneous deflection under fully cracked state at loading time t_0		
$\delta_e(t, t_0)$	Mid-span deflection at time t starting at loading time t_0		
ζ	Interpolation coefficient		
ξ	Time-dependent factor		

CRedit authorship contribution statement

Aloys Dushimimana: Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **José Sena-Cruz:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **João Miguel Pereira:** Writing – review & editing, Visualization, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Luís Correia:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices

Table A.1

Key model results for the slabs under sustained load in E1 to E6 environments.

Param.	EBR	NSM	EBR-MA	EBR-GA	EBR	NSM	EBR-MA	EBR-GA
	E1-conditioning				E2-conditioning			
D_0	7.2647	13.5231	4.7653	5.1536	9.4889	12.6819	5.4962	5.1283
D_1	1.8309	2.3650	1.8319	2.6272	1.00e−12	1.00e−12	3.9435	3.3971
$\tau_1 D_1$	342.2054	5862.43	342.82	239.66	16.5334	1075.93	585.78	580.9732
D_2	3.1567	3.7675	4.5573	3.1844	2.5694	1.5462	1.3709	1.0182
$\tau_2 D_2$	58363.21	55589.77	1459.09	47323.47	472.9225	5550.07	44416.40	7756.48
D_3	1.8018	2.1368	1.1968	5.314e−5	1.669e−5	1.00e−12	0.4227	2.859e−5
$\tau_3 D_3$	2.2529	334.89	1.0000	1828.23	493.5755	1878.24	1076.56	2698.51
D_4	1.8975	4.859e−4	1.8850	1.4801	0.8384	3.9354	4.994e−5	4.964e−4
$\tau_4 D_4$	7061.91	5290.77	8589.53	5289.19	3819.75	470.7732	4165.75	4152.81
δ_{50Y}	15.95	21.79	14.01	12.45	12.90	18.17	11.24	9.55
R^2	0.96	0.99	0.96	0.99	0.98	0.96	0.96	0.96
RMSE	0.32	0.11	0.28	0.14	0.25	0.26	0.26	0.22
MAE	0.15	0.09	0.14	0.10	0.17	0.15	0.14	0.12
R/D_f	2.15	0.54	2.51	1.23	2.50	1.45	2.45	2.30
	E3-conditioning				E4-conditioning			
D_0	8.5588	11.0189	5.1710	-	8.8557	12.2500	5.1701	5.5001
D_1	3.4698	4.1710	3.1246	-	4.5399	7.7281e−5	1.6592e−6	3.5074e−6
$\tau_1 D_1$	630.1644	692.9890	627.7601	-	2907.08	960.9987	436.5849	902.1717
D_2	4.7500	0.2140	4.0387	-	0.0040	3.5338	3.1303	4.3202
$\tau_2 D_2$	14090.70	706.7280	51913.79	-	3133.15	9650.65	31827.20	37911.79
D_3	1.2729	1.5430	6.573e−6	-	1.9768	2.1517	1.4346	1.4153
$\tau_3 D_3$	1.0000	1.1721	3644.89	-	2.0122	1.0000	1.0000	1.0000
D_4	1.847e−5	5.2857	3.5891	-	2.9615	3.9741	5.3410	5.0219
$\tau_4 D_4$	2585.31	13491.10	9045.68	-	37078.05	1904.34	2391.84	2544.95
δ_{50Y}	18.04	22.23	15.92	-	18.47	21.91	15.11	16.26
R^2	0.96	0.96	0.97	-	0.95	0.95	0.98	0.98
RMSE	0.30	0.35	0.29	-	0.47	0.53	0.37	0.34
MAE	0.25	0.30	0.26	-	0.22	0.28	0.18	0.20
R/D_f	1.67	1.56	2.04	-	2.67	2.42	2.53	2.28
	E5-conditioning				E6-conditioning			
D_0	8.1471	12.5321	5.9550	-	9.0172	11.5937	5.3095	4.7433
D_1	1.8343	2.0962	1.5000	-	2.746e−6	3.7990	2.6942	2.4650
$\tau_1 D_1$	313.8565	235.5807	242.5035	-	1231.180	2005.16	1495.55	1684.28
D_2	4.6254	6.3835	6.6086	-	3.5514	5.8535	4.5977	6.8799
$\tau_2 D_2$	27117.27	35298.64	36617.81	-	34001.96	39432.84	13889.72	66579.82
D_3	2.0957	2.8354	2.1865	-	1.4223	1.9528	1.2439	1.1496
$\tau_3 D_3$	5.0170	4.7823	3.8052	-	3.7699	4.1360	2.8955	19.6797
D_4	1.6142	2.7817	2.0676	-	3.4837	4.118e−4	4.741e−5	2.0814
$\tau_4 D_4$	6690.62	6229.57	4449.64	-	2318.92	2858.09	2971.59	9225.76
δ_{50Y}	18.31	26.63	18.32	-	17.48	23.20	13.85	15.39
R^2	0.97	0.97	0.97	-	0.99	0.99	0.99	0.99
RMS	0.37	0.55	0.47	-	0.23	0.27	0.36	0.08
MAE	0.25	0.40	0.31	-	0.15	0.16	0.24	0.06
R/D_f	2.11	2.19	2.84	-	1.40	1.24	2.57	0.54

Notes: $D_{i,i=0,4}$ and $\tau_i D_{i,i=1,4}$ are the coefficients defining elastic and viscous components of the generalized Kelvin model; δ_{50Y} is the deflection prediction at 50 years; R^2 : coefficient of determination, RMSE: Root Mean Square Error, MAE: Mean Absolute Error, R/D_f: error percentage (RMSE/maximum deflection).

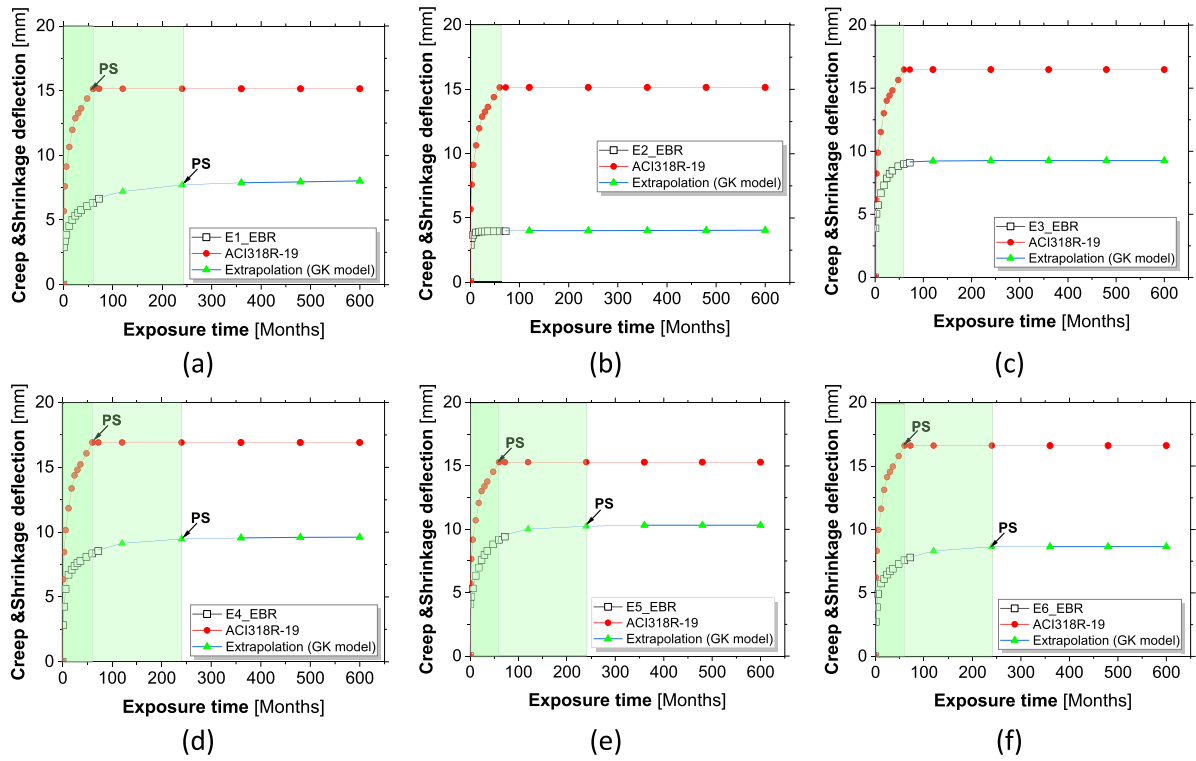


Fig. A.1. Time-dependent deflections (up to 50 years) due to creep and shrinkage effects for the slabs with EBR system under: (a) E1, (b) E2, (c) E3, (d) E4, (e) E5, and (f) E6 conditioning.

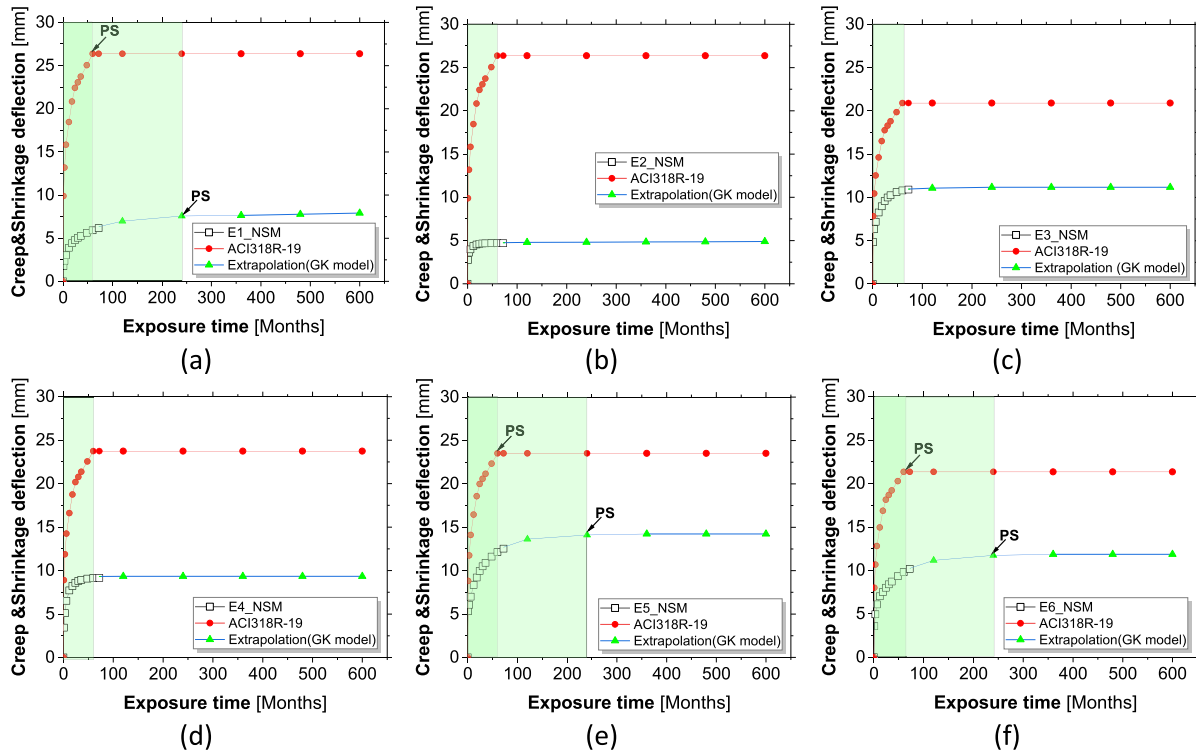


Fig. A.2. Time-dependent deflections (up to 50 years) due to creep and shrinkage effects for the slabs with NSM system under: (a) E1, (b) E2, (c) E3, (d) E4, (e) E5, and (f) E6 conditioning.

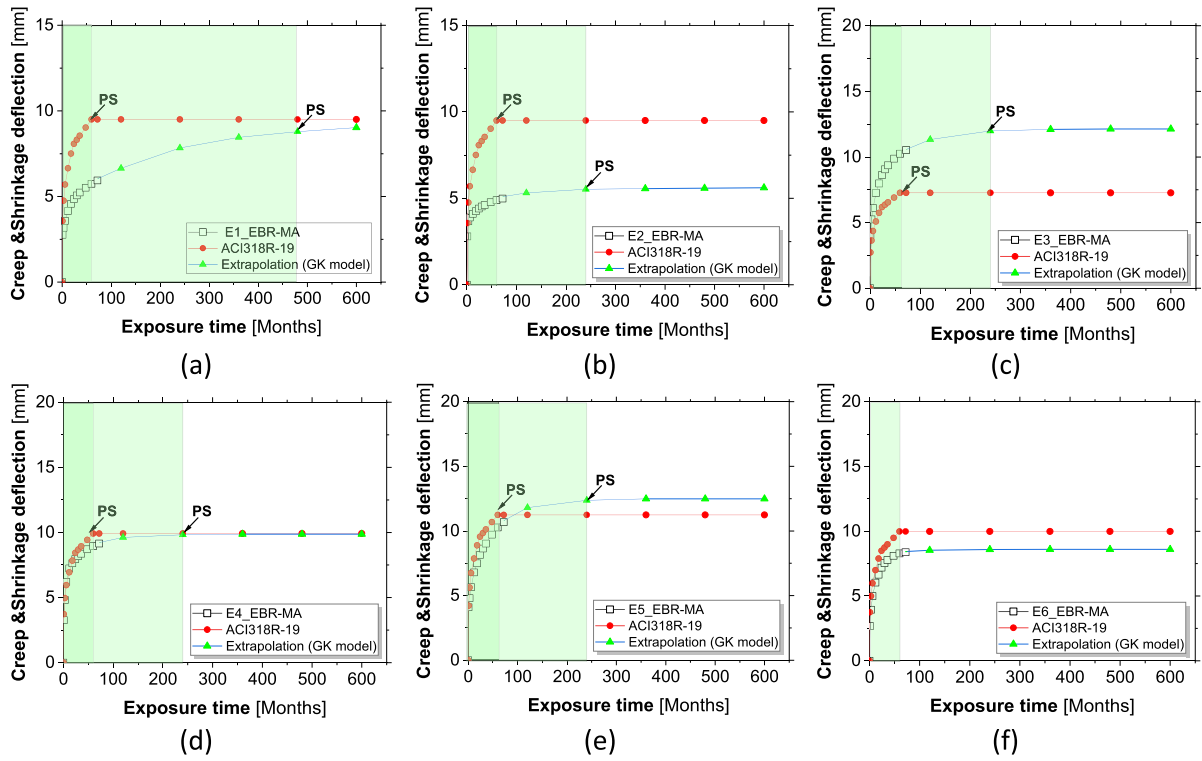


Fig. A.3. Time-dependent deflections (up to 50 years) due to creep and shrinkage effects for the slabs with EBR-MA system under: (a) E1, (b) E2, (c) E3, (d) E4, (e) E5, and (f) E6 conditioning.

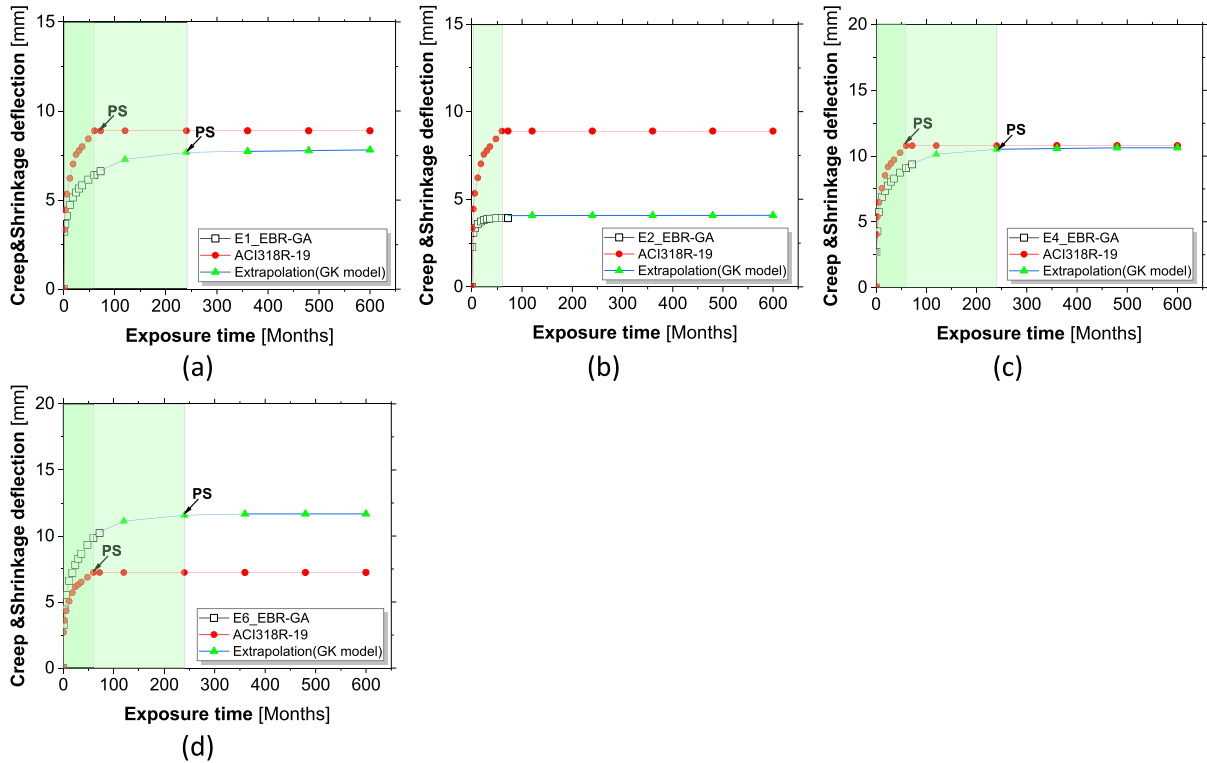


Fig. A.4. Time-dependent deflections (up to 50 years) due to creep and shrinkage effects for the slabs with EBR-GA system under: (a) E1, (b) E2, (c) E3, and (d) E4 conditioning.

Data Availability

Data will be made available on request.

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