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Comparison Analysis of Free Shrinkage Strains of Reinforced Concrete Box Girder Bridges Repaired With Concrete Overlays

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Abstract - When damaged bridges are repaired with new concrete overlays, the interface between new and old concrete restraints the high shrinkage of the overlay, leading to the development of tension stresses in the overlay, compression and bending stresses in the substrate, and shear stresses across the interface [1]. These stresses lead to cracks, through which corrosion and unbonding of the steel reinforcement is induced, and consequently cause failure of the repairs and compromise the static and dynamic performance of the repaired infrastructure [2]. In this study a numerical model was developed to predict the development of free shrinkage strains of reinforced concrete box girders repaired with overlays of different thickness and concrete compressive strengths to estimate the magnitude of the involved restrained stresses. The influence of the variability of the environmental humidity is also explored. Results show that for a typical 250 mm- thick overlay with concrete compressive of 30 MPa, and environmental humidity equal to 0.5, the maximum free shrinkage strain in the overlay after three years is estimated to be 529 $\mu\varepsilon$, which corresponds to 78% of the ultimate free shrinkage strain, ε_{sh_∞}. Over the same time frame, increasing the environmental humidity to 0.75 gives maximum shrinkage strains of 68% ε_{sh_∞}. Similarly, decreasing the thickness of the overlay to 150 mm leads to the development of free shrinkage strains of magnitude about 81% ε_{sh_∞}after three years. Finally, considering an Ultra High Performance Concrete overlay generates slightly smaller maximum strains than regular concrete: the predicted value of the maximum free shrinkage strain for the overlay is around 71% ε_{sh_∞}. Although these findings may be limited by the chosen geometry, they generally show that changes in the environmental factors and material properties affect the maximum free shrinkage strain. Particularly, a more humid external environment, a higher strength concrete and a thicker overlay reduce the susceptibility to cracking of the overlay with respect to the baseline case study.

Keywords**:** Overlay, Concrete, Bridge, Deck, Shrinkage, Strain, Humidity, Box girder

1. Introduction

The aging of reinforced concrete (RC) structures is one of the biggest concerns in civil and earthquake engineering since billions of dollars are spent annually on deck repairs and replacements, and corrosion and damage inevitably affect the seismic performance of RC infrastructure. When the deck of a bridge is chloride-contaminated/distressed and a new wearing surface is necessary, the damaged top layer is usually replaced with a new concrete overlay. This is one of the most common rehabilitation methods for bridges which are 10 years or older [3] but it involves two main risks, namely debonding and cracking of the overlay [4] [1]. Cracks tend to develop in concrete overlays as the new concrete layer changes in volume during the drying process. Tensile stresses form in the overlay because of such change in volume (shrinkage), which is however restrained by the existing substrate. Consequently, cracks will open in the concrete overlay when the tensile stresses exceed the tensile strength of the concrete.

Corrosion and unbonding of the steel reinforcement are induced through the cracks, leading to failure of the repairs and compromising the structural performance of the repaired RC infrastructure [2]. Investigating the risk of cracking in concrete overlays is indeed of critical importance in civil and earthquake engineering, because the service life of bridges is reduced by the presence of cracks in the deck and their seismic performance is significantly affected. In addition, the large maintenance and repairing costs associated to aging RC infrastructure usually burden significantly on the management of a country infrastructure network [5]. It is therefore necessary to accurately predict the stresses that are developed in RC bridges after repairs in order to avoid early cracking of the new concrete overlay and to ensure a desirable monolithic behaviour of the system. A reliable preliminary estimation of the magnitude of such stresses comes from the assessment of the free shrinkage strains generated in repaired RC bridges after casting the fresh layer of concrete [6]. To this end, this paper presents the results of a numerical model developed to predict the free shrinkage strains under different environmental conditions and for varied geometric and material properties.

2. Research significance

A comprehensive evaluation of the structural safety of RC bridges repaired with fresh cast-in place overlays is of paramount importance to understand the durability issues of current concrete repair practices. The high percentage of failed bridge repaired with overlays shows that much uncertainty still exists about this type of structural rehabilitation. Moreover, it was observed that concrete overlays are sensitive to moisture loss from the new concrete layer [7]. As such, the moisture distribution, water migration and the related drying shrinkage processes need to be accurately described through numerical and analytical formulations. To aid in the estimation of shrinkage strains, a numerical model is proposed in this paper. A comparison analysis of free shrinkage strain of RC box girder bridges repaired with concrete overlays is presented in the following. Among all types of bridges, a concrete box girder bridge was specially selected for this study because this type of structure generally requires more deck rehabilitation works [8]. Additionally, RC box girder bridges often show unforeseeable and excessive multi-decade deflections, with a very slow initial rate of the deflection, which then grows unexpectedly rapidly with time [9] [10] [11].

While a previous study by the authors carried out a two-dimension finite element analysis aimed at evaluating the humidity and free shrinkage strain profiles of a box girder bridge repaired with a concrete overlay of the same compressive strength of the substrate at different times, from the day of casting until 50 years later [12] [13], this study sets out to provide a more systematic understanding of the factors that influence the behaviour of reinforced concrete box bridges repaired with concrete overlays. The ultimate objective of this study is to provide valuable insight that could prevent the cracking of the deck due to rehabilitation solutions.

3. Analytical model

A two-dimension finite element analysis of a reinforced concrete box girder bridge repaired with a new concrete overlay is carried out to evaluate the humidity profiles at different time steps, up to 50 years after casting. The finite elements consist of three-node constant strain triangles (CST). The moisture diffusion that occurs after the casting of the overlay on the existing substrate is the first phenomenon that needs to be described to then evaluate the free shrinkage strains of the rehabilitated box girder bridge.

The predicted humidity profiles include the drying humidity, h_d, which was evaluated with Fick's Second Law of Diffusion (Equation 1), and the autogenous humidity (h_a) effects, which are computed with Equation 2.

$$\frac{\partial h_d}{\partial t} = \nabla\left[D(h_d)\vec{\nabla}(h_d)\right]U(t-t_0) \qquad (1)$$

$$h_a = 1 - a_1\left[1 - e^{(-a_2 t^{n_a}}\right]U\left(t - \frac{2}{3}t_0\right) \quad (2)$$

In Equation 1, $D(h_d)$ is the concrete diffusivity and $U(t-t_0)$ the Heaviside unit step function; in Equation 2, a_1, a_2, and n_a are empirically derived coefficients [6].

The diffusivity of the concrete is modelled with Equation 3, [14]:

$$\frac{D(h_d)}{D_1} = a_0 + \frac{(1-a_0)}{1+\left(\frac{1-h_d}{1-h_c}\right)^{n_s}} \qquad (3)$$

where the values of parameters D_1, a_0, h_c, and n_s are taken from literature and based on test results [6][15].

An initial assumed drying humidity value is assigned to every node; a one-dimensional finite element analysis is carried out along the length of the bridge to accurately predict the humidity value in the middle of the bridge and to use this value as a boundary condition for the internal edge of the box girder. The drying humidity is then evaluated with a transient analysis in two dimensions: the finite element equations are obtained by applying Galerkin's weighted residual method. An implicit scheme with a backward difference approximation for the time term is then applied because of its unconditional stability. Moreover, since the diffusion coefficient is non-linear, the solution algorithm follows an iterative procedure. The final humidity, h, comprising drying and autogenous effects, is then assessed.

Furthermore, free shrinkage strains, ε_{sh}, are evaluated with Equation 4 considering the rate of shrinkage change a function of humidity change and taking into account both drying and autogenous humidity. Aging effects are included within the k_{sh} parameter.

$$\frac{\partial \varepsilon_{sh}}{\partial t} = \varepsilon_s^0 k_{sh} \frac{\partial h}{\partial t} \qquad (4)$$

Following the estimation carried out in a previous paper [6] the value of the ultimate long-term shrinkage strain for a theoretical internal humidity of zero, ε_s^0, is taken to be equal to 1.3 ε_{sh_∞}. The ultimate free shrinkage strain, ε_{sh_∞}, is instead evaluated with Equation 5, [16]:

$$\varepsilon_{sh_\infty} = -\alpha_1 \alpha_2 [(1.9)\ 10^{-2} w^{2.1} f_{cm}^{-0.28} + 270] 10^{-6} \qquad (5)$$

where parameters α_1 and α_2 depend on the type of cement and curing, respectively, f_{cm} is the mean compressive strength of concrete and w is the water content.

The model was validated by applying the algorithm to the infinite slab rehabilitated with a concrete overlay presented in a previous study [6]which results were compared with experimental results. Amongst the available commercial tools to run this analysis, Matlab was used because it provides the possibility to run a defined user optimization algorithm [17]. More details of the solution algorithm are presented in previous studies by the authors [12] [13].

4. Study cases

The research intends to evaluate the effect of different material, geometric and environmental factors on the final shrinkage strains. To this end, this study considers a concrete box girder bridge, specifically cross-section 2100-2 with a 61 m span detailed in [18] with a 225 mm deck, and selects different possible scenarios in order to compare the importance of various influencing factors. The choice of different scenarios was based on the results of the influencing factors from the literature [19]: this sensitivity analysis took into consideration concrete overlays on different substrates (rectangular slab and steel beams) and it was based on a one-dimensional finite element analysis.

The reference case is presented in a previous paper by the authors [12]and it involves an overlay thickness of 250 mm to show the effects of an extensive deck rehabilitation work, and a concrete compressive strength equal to 30 MPa. The environmental relative humidity, h_{env}, is assumed equal to 0.5.

The second case presents an overlay of the same thickness and concrete compressive strength of the reference case, but in this scenario the environmental relative humidity is taken equal to 0.75, to investigate the influence of the external humidity on repair works.

The third case displays the same concrete compressive strength and environmental humidity of the reference case, but in this scenario the thickness is reduced to a more common value of 150 mm, in order to highlight the importance of the selection of an appropriate overlay thickness.

The fourth scenario shows a rehabilitation performed with an 80 mm thick overlay in Ultra High-Performance Concrete (UHPC), with a concrete compressive strength equal to 150 MPa. The environmental humidity is maintained equal to 0.5.

The mesh size is around 50 mm for cases 1-3, while for case 4 it was reduced to 35 mm. For all scenarios, a 10 mm dummy layer is added to the cross-section to allow the use of Dirichlet boundary conditions.

The scenarios are summarised in Table 1.

Table 1. Study cases.

Study case	**Thickness (mm)**	**f_c' (MPa)**	h_{env}
1	250	30	0.5
2	250	30	0.75
3	150	30	0.5
4	80	150	0.5

The initial internal humidity is taken equal to 1 for the nodes in the overlay region; on the other hand, the nodes of the old substrate are assumed to have an internal humidity of 0.55 for cases 1, 3 and 4 and 0.675 for case 3. The humidity inside the box of the bridge girder is taken as 0.6, as evaluated in a previous study with a one-dimensional finite element analysis along the bridge length [12].

The cement content is taken equal to 350 kg/m^3 and the water content to 161 kg/m^3 [6] for cases 1 to 3, while for case 4 the cement content is taken equal to 712 kg/m^3 and the water content to 109 kg/m^3 [8]. A four days curing time is assumed for each scenario. The equations presented in the previous sections are assumed to be valid for high performance concrete as well, even if experimental tests are scarce.

5. Results

5.1 Humidity profiles

The changes in humidity at casting and after 10 years are shown in Figure 1 for the entire cross section. Drying humidity and autogenous humidity effects are both taken into account in the proposed analysis. Figure 1 shows that the predicted average humidity of the entire cross section after 10 years is about 5-10% higher than the environmental humidity for scenarios 1, 3 and 4; after 50 years there is a trend inversion, and the average humidity of the cross section presents a decrease smaller than 6% for these same cases. In the second scenario instead, the cross section in a more humid environment behaves differently, showing from the beginning a decrease in humidity of about 7% after 10 years which becomes close to 11% after 50 years. However, even with slight differences, these results convey the general idea that the cross section almost reaches its equilibrium after 10 years in all scenarios, regardless of geometric and material properties and environmental conditions [12].

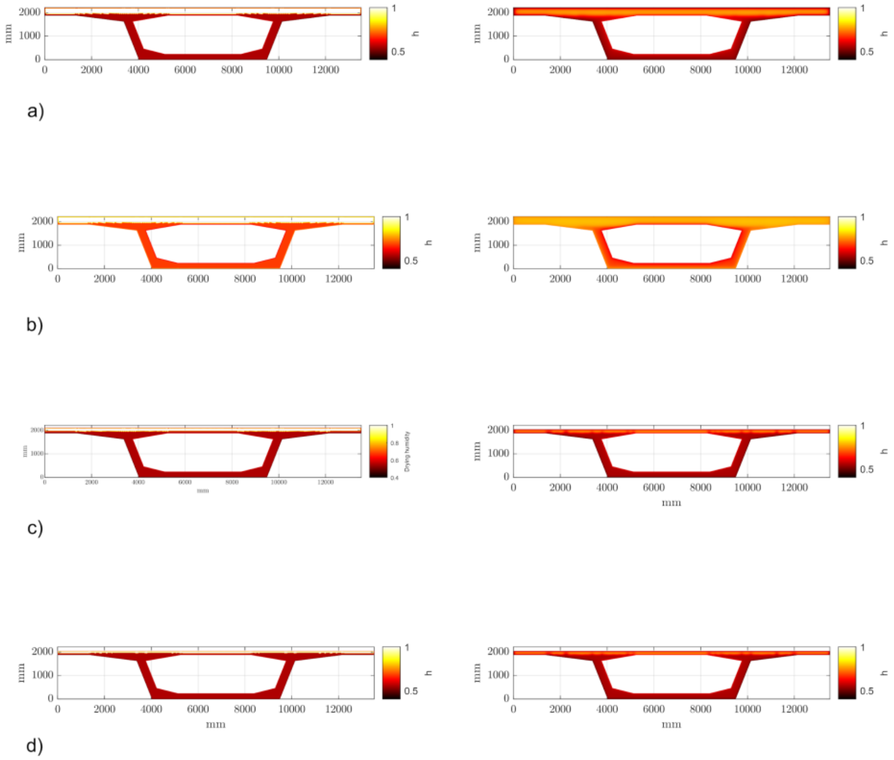


Figure 1: Humidity profiles at casting (on the left) and after 10 years (on the right):
a) Case study 1; b) Case study 2; c) Case study 3; d) Case study 4.

Detailed humidity results for the nodes in the deck region are presented in Figure 2. The horizontal line indicates the overlay boundary.

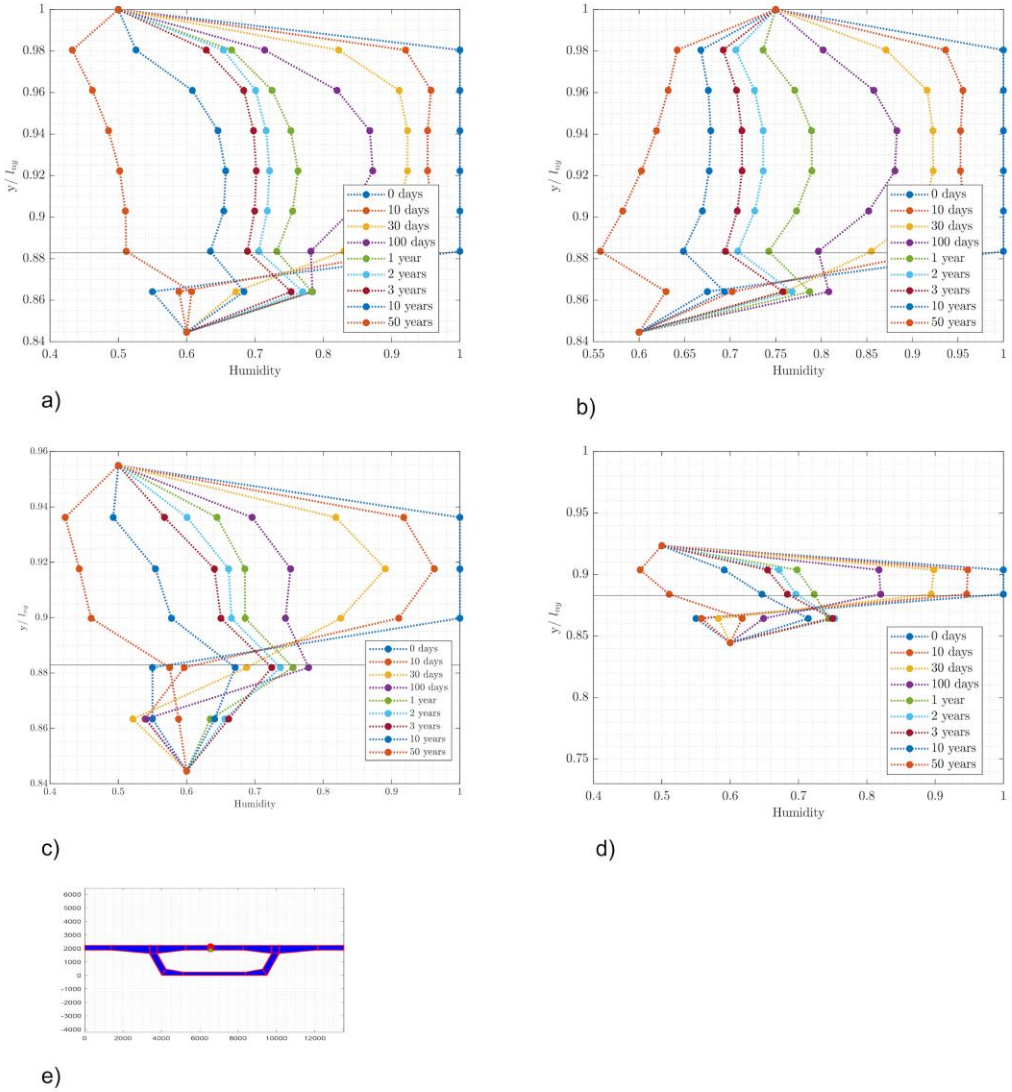


Figure 2: Humidity profiles at midspan in the deck for selected nodes at different time steps:
a) Case study 1; b) Case study 2; c) Case study 3; d) Case study 4; e) Location of selected nodes.

The non linearity of the humidity profiles and the difference in moisture between the overlay and the substrate observed in Figure 1 and in Figure 2 may lead to surface cracks in all scenarios, since this gradient influences the drying shrinkage and increases the tensile stresses. The substrate at the beginning of the analysis has a relative humidity similar to the one of the environment: 0.55 in cases 1,3 and 4 and 0.675 in case 2. After casting of the overlay, the substrate becomes more humid because of water migration during the drying process, then it becomes stable at a value just slightly higher (for cases 1, 3 and 4) or lower (for case 2) of the initial relative humidity. The humidity in the overlay goes instead from a value equal to 1 after concrete casting, to values closer to the external humidity: after 10 years the decrease in humidity at the overlay mid-depth at mid-span (as shown in Figure 2) is around 40% for all scenarios, with the highest predicted decrease for case 3.

Taking into consideration average values of the predicted relative humidity, the difference percentage between the overlay and the substrate is smaller than 7% for all scenarios after 10 years; however, after 50 years the selected study cases show different behaviors: case 1 and case 4 present a difference percentage of about 16-17%, while this difference percentage is about 9% for case 2 and 24% for case 3. These gradients suggest that the case with the highest free shrinkage strains would be case 3, the one with the thin overlay and the same concrete compressive strength of the reference case.

The rate of variation in humidity decreases with time, as it can be observed from Figure 1 and Figure 2. It should be noted that even if the equilibrium of the system is almost reached after 10 years, the humidity slowly continues to decrease, showing that the drying process carries on even with a low diffusion coefficient.

5.2 Free shrinkage strain profiles

After the assessment of the humidity profiles, the free shrinkage strain distribution is evaluated. Figure 3 shows the strain profiles for the different scenarios at 10 days after casting and after 10 years.

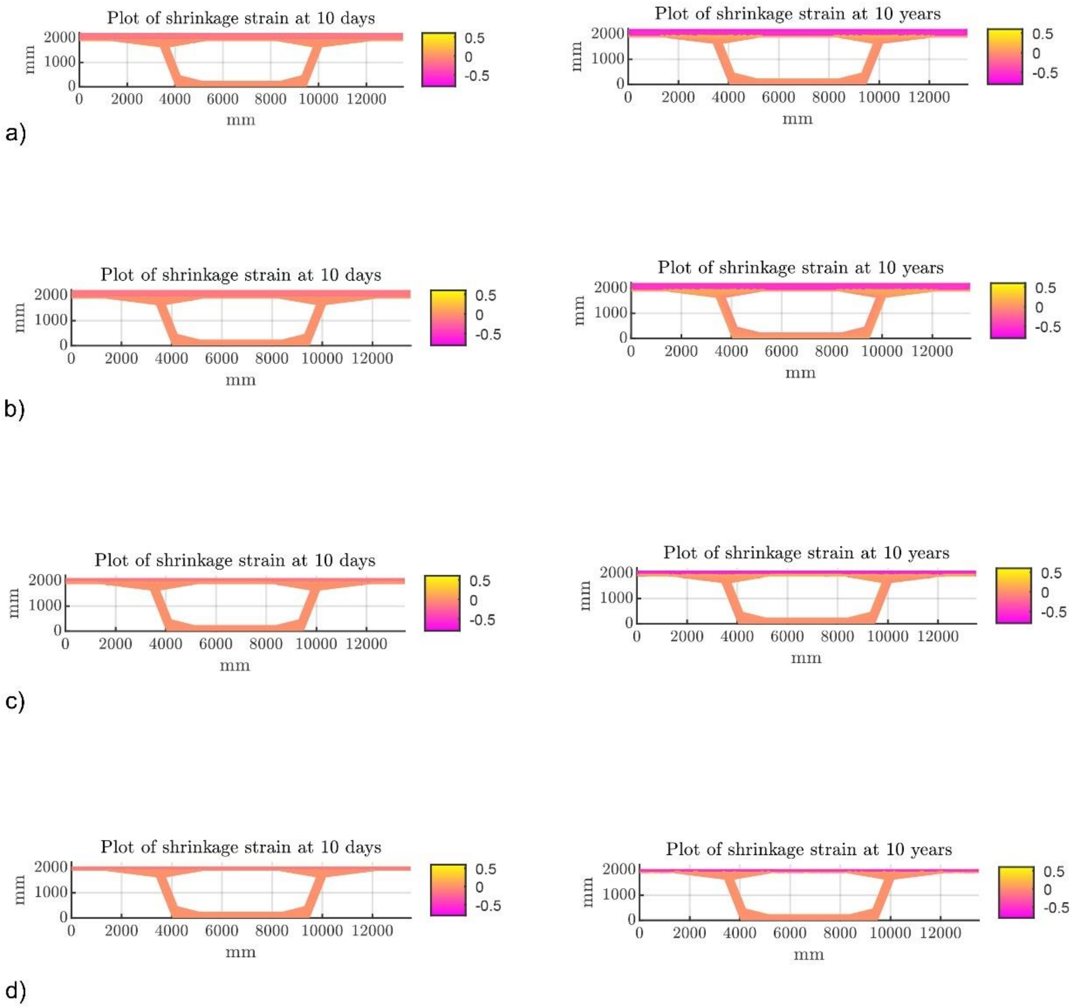
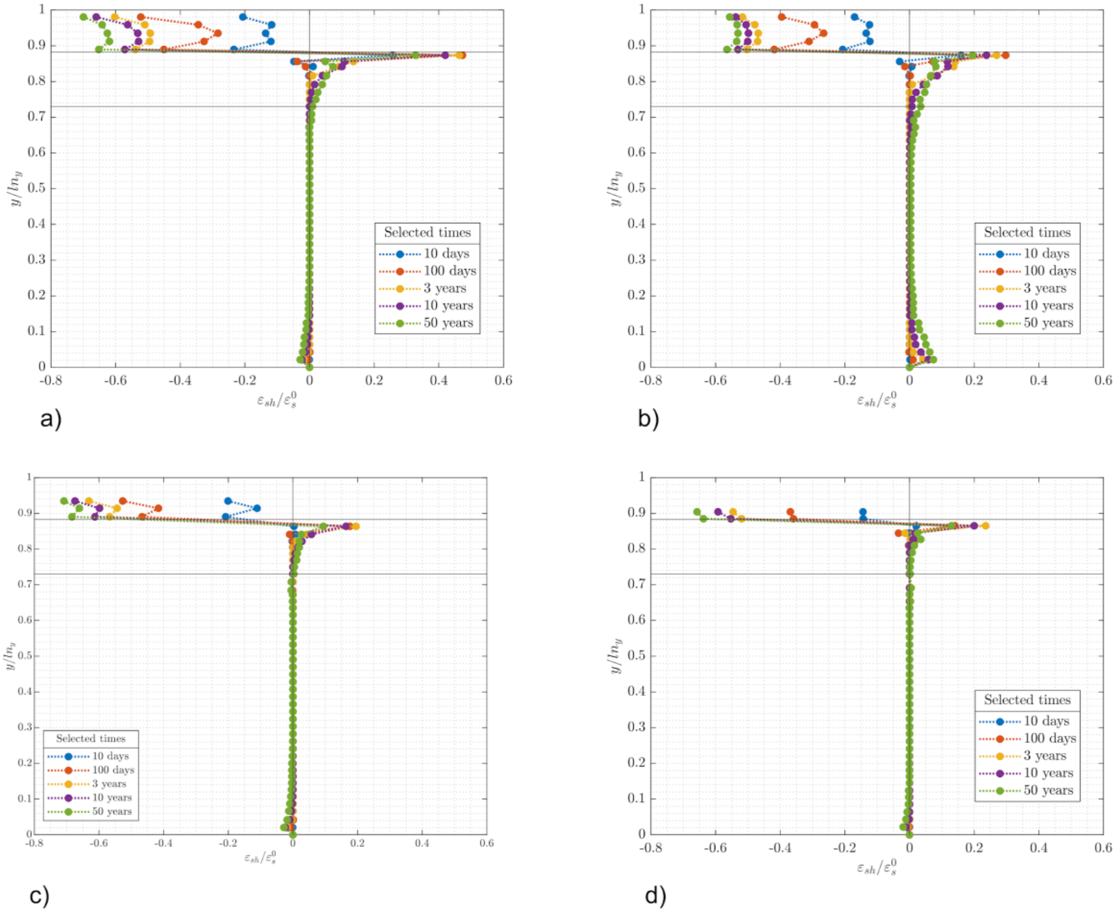


Figure 3: Free shrinkage strain distributions 10 years after casting (on the left) and after 10 years (on the right):
a) Case study 1; b) Case study 2; c) Case study 3; d) Case study 4.

The normalized free shrinkage strains profiles for selected nodes at different times are presented in Figure 4: the first horizontal line from the bottom represents the beginning of the deck while the second horizontal line shows the position of the overlay boundary.



a) b) c) d)

Figure 4: Free shrinkage strains along one web:
a) Case study 1; b) Case study 2; c) Case study 3; d) Case study 4.

The shrinkage strain results for the overlay layer are detailed in Table 2 for 100 days' and 10 years' time frames: the 100 days step has been chosen to show the behaviour after quite some time after setting, while the 10 years value has been used because the humidity profiles almost reach equilibrium at this time.

Table 2: Normalized free shrinkage values $\varepsilon_{sh}/\varepsilon_s^0$ for all cases at selected time steps.
The maximum values are recorded at the top or bottom of the overlay layer.

Study case	**100 days**		**10 years**	
	Max.	**Mid-depth**	**Max.**	**Mid-depth**
1	0.53	0.30	0.65	0.55
2	0.40	0.23	0.55	0.50
3	0.53	0.43	0.68	0.60
4	0.38	0.35	0.60	0.55

As it can be observed in Figure 4, all cases present swelling at the interface between the new and old concrete and increasing compressive strains with time. The maximum swelling at the interface between the new layer and the old concrete is predicted for case 1 to be 0.475 ε_s^0 after 100 days; a more humid environment proves to be slightly beneficial, as shown with the 0.30 ε_s^0 value in case 2 at the same time step of 100 days. Cases 3 and 4 present the smallest swellings of all scenarios, with predicted values close to 0.20 ε_s^0 after 3 years.

A noticeable difference can be observed in Figure 4 for cases 1-3 between the maximum shrinkage strains at the overlay boundary and at the overlay mid-depth. This shrinkage strain differential in the overlay is due to the non-linearity of the humidity profiles, and decreases with time, as expected. The largest strain gradient is predicted for the reference case, which presents a percentage difference of about 55% between the top layer and the overlay mid-depth 100 days after casting. The decrease of strain gradient with time leads to a 17% percentage difference between the top of the cross section and the mid-depth of the overlay for case 1 after 10 years, while cases 2 and cases 3 and 4 show a difference of about 10%: these lower gradients are due to the higher environmental humidity (for case 2) and to the casting of a thinner overlay (for cases 3 and 4).

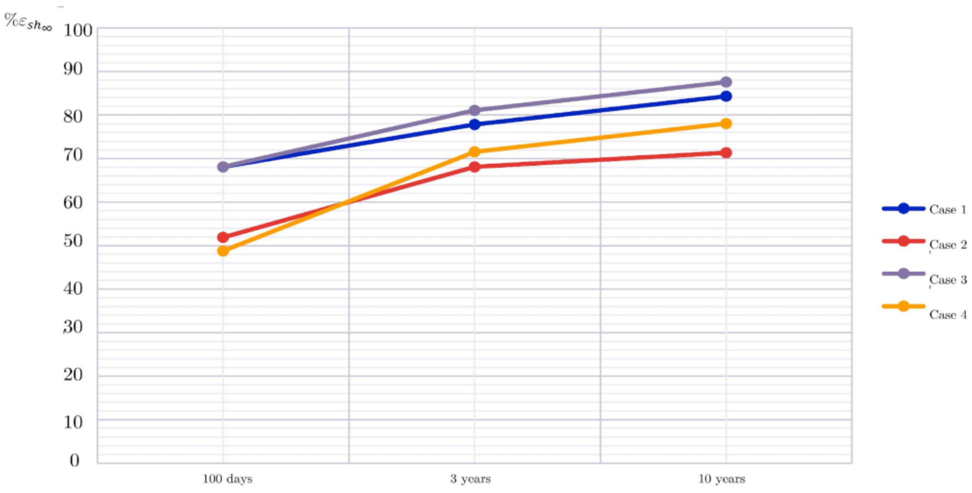


Figure 5: Maximum free shrinkage strains in the overlay at selected time steps as percentage of the ultimate free shrinkage strain ε_{sh_∞}.

The maximum free shrinkage strain values for selected time steps are presented in Figure 5 as a percentage of the ultimate free shrinkage strain ε_{sh_∞}. At the top and bottom of the overlay, where the maximum shrinkage strains are recorded, the cross section studied in the reference case reaches 68% ε_{sh_∞} after 100 days; the scenario with a higher environmental humidity (case 2) and with the UHPC overlay (case 4) show smaller values, 52% ε_{sh_∞} and 49% ε_{sh_∞} respectively. After 10 years, case 3 presents the highest value of maximum shrinkage strain, 88% ε_{sh_∞}, which is about 4.2% higher than the reference scenario value. The use of UHPC reduced the maximum shrinkage strain in the overlay, with a decrease of 8.1% in comparison to case 1. A higher environmental humidity proves to be the biggest influencing factor, with maximum shrinkage strain values about 13% smaller than the ones of the reference case.

Moreover, the rate of free shrinkage strain change for the time frame between 10 days and 100 days is significant in all scenarios: the maximum value is recorded for case 3 in which the increase with time is about 163% showing that the decrease in thickness is disadvantageous. This result indicates that cracking of the overlay is very likely to occur early after casting.

The rate of free shrinkage strain change decreases with time: between the 100 days’ time step maximum free shrinkage strains and the values predicted after 3 years, the difference percentage is about 15-20% for cases 1-3; after 50 years the difference with the 10-year time frame is lower than 8% for the same cases. Scenario 4, which includes a UHPC overlay, shows instead a higher shrinkage increase at the beginning, starting with a difference percentage of about 38% between the 100 days and the 3-year time steps, but it then reaches the same 8% difference between the 50 years and 10 years' time steps of the other scenarios.

6. Conclusions

This research assessed the humidity and free shrinkage strain profiles of box girder bridges repaired with concrete overlays. The influencing factors considered in this study are the external environmental humidity (case 2), the overlay thickness (case 3) and the concrete compressive strength associated with a thinner overlay, as in the case of UHPC overlays (case 4). Even if a restrained stress analysis considering creep effects would provide a more complete understanding of the behaviour of box girder bridges repaired with different types of concrete overlays, the results presented in this research clearly show the likelihood of overlay cracking under varied geometric, material, and environmental conditions, and provide valuable insight for choosing the appropriate deck repair of a box girder bridge of similar dimensions.

The following conclusions are drawn:

- The humidity gradient is a reliable indicator of the scenarios that will present higher free shrinkage strains;
- The percentage of ultimate free shrinkage strain reached after 10 years is minimum for the case set in a most humid environment, proving that the humidity gradient is a highly important factor which should be taken into account in structural designs of repairs.
- Thinner overlays, such as the one of case 3, presented a poorer performance, as previously observed in literature [5], [19].
- Whilst the results of the UHPC overlay of case 4 do not show a significant improvement, more analyses are deemed to be necessary, since the high concrete compressive strength has an important role in the restrained stress evaluation.

The humidity and free shrinkage strain profiles of all cases almost reach equilibrium after 10 years, hence an analysis along this time frame should be appropriate in most cases, saving computational time, as also observed in a previous paper by the authors [12].

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