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Towards modelling the long-term behavior of prestressed CFRP strips subjected to elevated temperatures

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ABSTRACT: Prestressed Carbon Fiber Reinforcement Polymer strips and epoxy adhesives can reach high temperatures when they are used as a reinforcement to strengthen the upper side of lateral cantilevers belonging to highway concrete box-girder bridges. Such reinforcements are directly exposed to elevated temperature scenarios due to the sealing process and the application of the asphalt layer during the construction or later due to the sun heating during service. The paper has two main objectives. On the one hand, an analytical model has been developed to evaluate the stress state of a prestressed strip/epoxy/concrete joint. On the other hand, an analysis of such joint under a high temperature scenario has been performed depending on the epoxy temperature level. The theoretical results have been compared with some experimental measurements. The simulation of a high temperature scenario seems to be related to a decrease of the maximum shear stress and an increase of the effective bond length in the strip/epoxy/concrete joint.

1 INTRODUCTION

Externally bonded (EB) prestressed Carbon Fiber Reinforced Polymer (CFRP) strips are frequently used as an additional reinforcement to strengthen reinforced concrete structures directly exposed to elevated temperatures. In the framework of a research project on the durability of EB CFRP reinforcements in bridge construction, an experimental campaign was performed to study the influence of elevated temperature on prestressed CFRP strips with the gradient anchorage (Michels et al. (2013)). The gradient anchorage method is a technique that avoids mechanical anchorage systems for prestressed CFRP strips and is based on the application of a local curing of the epoxy adhesive accelerated by heat and followed by the release of the prestress force in different stages.

One of the most important applications of these prestress reinforcements is related to the strengthening of the upper side of lateral cantilevers of highway concrete box-girder bridges. As a first approach of the gradient anchorage system, an experimental campaign in small scale specimens has been done to assess the long-term behavior of the gradient anchorage at elevated temperatures. The investigation included several tests on prestressed CFRP strips anchored to a concrete block and subsequently exposed to an elevated temperature scenario. A detailed description of these tests is presented in Gallego et al. (2015).

The paper is divided in two different parts. Firstly, an analytical model has been proposed in order to study the stress state of a strip/epoxy/concrete joint after the releasing stage. Then, the behavior of the strip/epoxy/concrete joint under an elevate temperature scenario was studied.

2 STAGE 1: ANCHORING OF THE PRESTRESS FORCE

2.1 Introduction

In this section the stress state of a strip/epoxy/concrete joint after the releasing of the prestress force is studied. The three main phases of this anchoring stage (prestressing, curing and releasing) are represented in Figure 1. After fixing the concrete block to the reaction floor, the epoxy adhesive was applied onto the strip and it was placed on the top of the concrete block and connected to the hydraulic jacks with clamps at both ends. Thereafter, the CFRP strip was tensioned by an oil hydraulic cylinder and the prestress force was measured using load cells. Before to release the prestress force in one of the ends an accelerated curing of the epoxy adhesive was done. An Image Correlation System (ICS) has been used to monitor the strip displacements during the tests. A detailed description of the experimental campaign is described in Gallego et al. (2015).

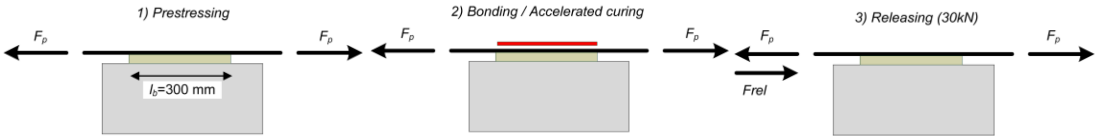

Figure 1. Anchoring of the prestress force: Prestressing, curing and releasing.

2.2 Analytical model to assess the stress state in the strip/epoxy/concrete joint

An analytical model to evaluate the stress state in the strip/epoxy/concrete after the releasing stage is presented in this section. For practical applications the gradient anchorage is designed considering an initial prestress force below a threshold value in order to assure that the strip displacements are still in the linear range and no cracks are formed in the concrete surface during the anchoring. When the strip/epoxy/concrete joint is still in the elastic range the shear stresses are transferred to the concrete block due to the elastic shear deformation of the epoxy adhesive.

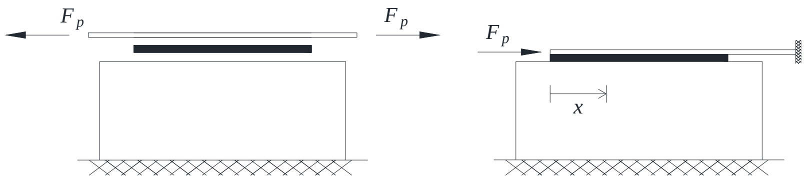

Figure 2. Stages of the gradient anchorage: (a) Prestressing and anchoring of the strip; (b) Release of the prestress force on one side of the concrete block.

To assess the stress state of the strip/epoxy/concrete system when the prestressed force is transferred, two stages have been considered according to Figure 2. The first stage is the application of the prestress force in the strip. In this stage the tensile stress in the strip is constant and can be estimated according to eq.(1) where $F_{p,0}$ is the initial prestress force and b_f

and t_f are the width and the thickness of the strip respectively. In this stage no shear stresses are generated.

$$\sigma_0 = \frac{F_{p,0}}{b_f t_f} \qquad (1)$$

The second stage is related to the release of the initial prestress force in one of the ends. In this stage the prestress force is transferred to the concrete block due to the elastic shear deformation of the epoxy layer. The remaining stress state in the joint after this stage is highly dependent on the transverse behavior of the epoxy adhesive.

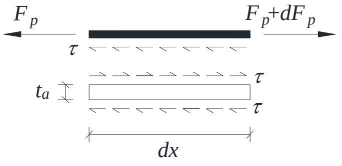

Figure 3. Stress state of an infinitesimal element during the releasing of the prestress force.

The stress state of an infinitesimal element in the second stage is represented in Figure 3.The equilibrium condition of such element is given by eq.(2) where F_p and τ are the strip force and the shear stresses in the infinitesimal element, respectively. In this stage the epoxy is considered to be in pure shear and eq.(3) can be used to evaluate the shear stress state in the joint, being K_{el} the elastic stiffness of the strip/epoxy/concrete joint and u the longitudinal relative strip displacement.

$$\frac{dF_p}{dx} = b_f \tau \qquad (2)$$

$$\tau = K_{el} u \qquad (3)$$

According to the strut-and-tie model presented in Czaderski (2012), the elastic stiffness K_{el} can be determined by eq.(4) where E_c and E_a are the elastic modulus of the concrete block and the epoxy respectively. Parameter t_a is the thickness of the epoxy layer and t_{ca} is the effective thickness of the concrete surface.

$$K_{el} = \frac{1}{4\left(\frac{t_{ca}}{E_c} + \frac{t_a}{E_a}\right)} \qquad (4)$$

The strip strain ε can be obtained by eq.(5). The strip force and the strip strain are related through eq.(6) where E_f and A_f are the elastic modulus and the area of the strip respectively.

$$\varepsilon = \frac{du}{dx} \qquad (5)$$

$$\frac{dF_p}{dx} = E_f A_f \frac{d\varepsilon}{dx} \qquad (6)$$

Substituting eq.(3) and eq.(6) in eq.(2), eq.(7) is obtained. The elastic behaviour of the second stage is governed through eq.(7) where α is a constant defined by eq.(8).

$$\frac{d^2u}{dx^2} - \alpha^2 u = 0 \qquad (7)$$

$$\alpha^2 = \frac{K_{el}}{E_f t_f} \qquad (8)$$

$$u = A\cosh(\alpha x) + B\sinh(\alpha x) \qquad (9)$$

The analytical solution of the differential equation is given by eq.(9), where A and B are two constants that have to be determined with two boundary conditions. The boundary conditions imposed to obtain both values are the following:

- The strip force at the end where the force is released has to be equal to the initial prestress force, i.e., F_p (x=0) = $F_{p,o}$.
- The strip force at the other end of the bond length has to be zero, i.e., F_p (x=L) = 0.

Imposing these two boundary conditions, the tensile stresses in the strip during the second stage can be calculated through eq.(10), being L the bond length.

$$\sigma_f = \frac{\sigma_0}{\sinh(\alpha L)}\sinh(\alpha x) \tag{10}$$

Considering the first stage where the initial tensile strip stress σ_0 is given by eq.(1), the tensile stress in the strip after release the initial prestress force is given by eq.(11). Eq.(12) and eq.(13) can be used to assess the shear stresses and the longitudinal strip displacements in the strip/epoxy/concrete joint respectively.

$$\sigma_f = \sigma_0 - \sigma_f = \sigma_0 - \frac{\sigma_0}{\sinh(\alpha L)}\sinh(\alpha x) = \sigma_0\left(1 - \frac{\sinh(\alpha x)}{\sinh(\alpha L)}\right) \tag{11}$$

$$\tau = \frac{\alpha F_{p,0}}{b_f \sinh(\alpha L)}\cosh(\alpha x) \tag{12}$$

$$u = \frac{F_{p,0}}{E_f A_f \alpha . \sinh(\alpha L)}\cosh(\alpha x) \tag{13}$$

For high prestress forces partial debonding of the strip can happen in the end of the strip where the force is released. This partial detachment can also occur if epoxy adhesives with high elastic modulus are used due to the lower ability of such adhesives to redistribute the shear stresses along the bond length during the releasing stage.

2.3 *Application of the model to the prestress force-release tests performed at Empa*

In this section the stress state of a strip/epoxy/concrete joint belonging to one of the tests performed at Empa is evaluated through the analytical model previously presented. The predicted results for the strip tensile stress and shear stress distributions are represented in Figure 4. According to Figure 4(Left) the value of the tensile stress in the strip varies from zero at the end where the prestress force is released (x=0 mm) to the initial tensile stress σ_0 at the other end of the bond length (x=300 mm).

The distribution of the shear stresses along the bond length is represented in Figure 4(Right) being the maximum value close to the end where the prestress force is released. The results obtained through this model are very sensitive to the value of the epoxy elastic modulus. For low epoxy elastic modulus values the joint has more capacity to transfer the prestress force during the releasing along the bond length due to the softer behaviour of the adhesive. For high values of this variable the epoxy behaviour is stiffer and the high shear stress concentration in one of the strip end can develop microcracks in the concrete surface and subsequently partial detachment of the strip.

The experimental results of the longitudinal strip displacements are represented and compared with the prediction given by the model in Figure 5. The model predicts with enough accuracy the tendency observed in the tests. The results presented in this section have been calculated considering a concrete block with an elastic modulus of 30 MPa and an epoxy layer with an elastic modulus of 1000 MPa and 3 mm thickness. This relative low value of the epoxy elastic modulus can be attained due to the elevated temperature reached in the epoxy after the curing period and before the releasing stage.

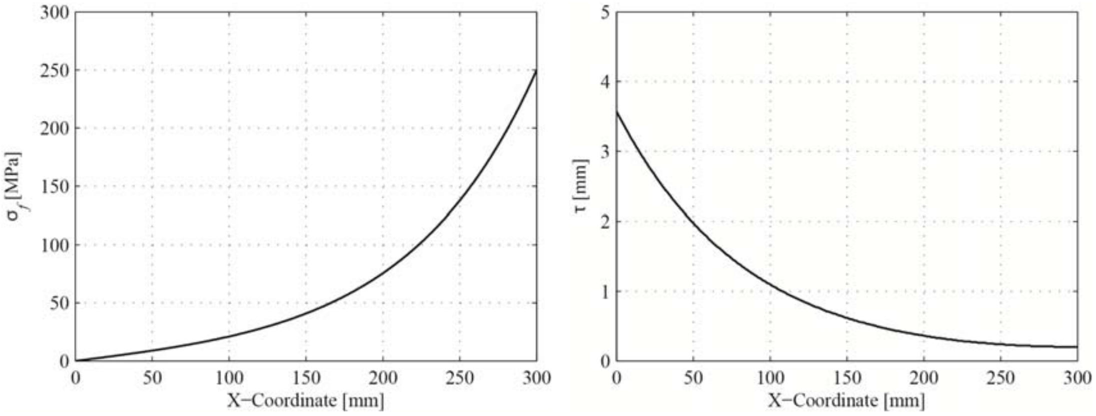

Figure 4. Stress state after the anchoring stage: (Left) Tensile stresses in the strip; (Right) Shear stresses along the CFRP/epoxy/concrete joint.

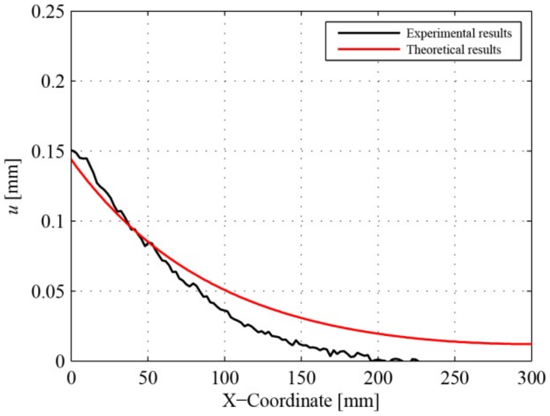

Figure 5. Strip slips after release the prestress force.

3 STAGE 2: BEHAVIOUR OF A GRADIENT ANCHORAGE DURING THE SIMULATION OF AN ELEVATED TEMPERATURE SCENARIO

3.1 Introduction

Experimental measurements have shown that for EB prestressed CFRP reinforcements used to strengthen the upper side of lateral cantilevers belonging to highway concrete box-girder bridges the critical high temperature scenario is reached during the application of the mastic asphalt layer. In order to experimentally simulate this situation, the strip was heated by electric current following the temperature-time curve represented in Figure 6(Right). This curve is related to the epoxy temperature measured during the simulation of a typical asphalt scenario and was obtained by a thermocouple placed in the epoxy adhesive underneath. As in the releasing stage, an ICS was used to measure the strip displacements during the heating.

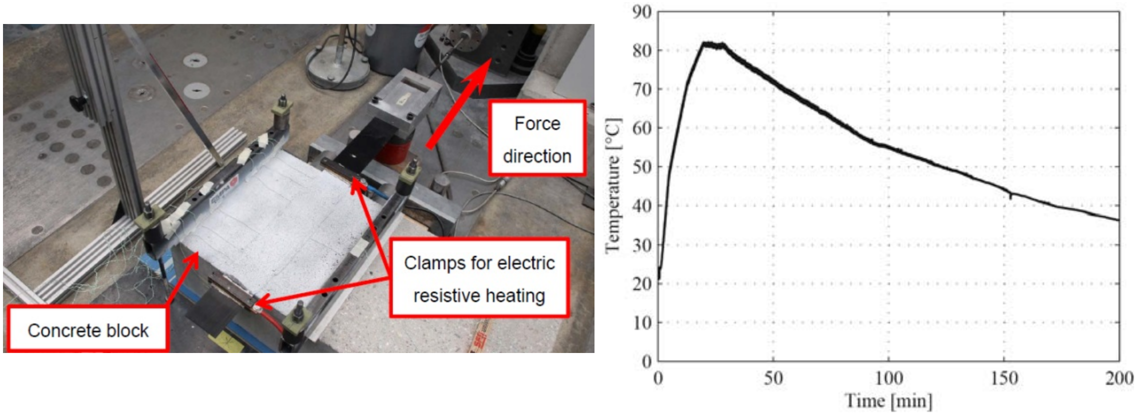

Figure 6. Setup for the temperature stability tests for prestressed CFRP strips.

3.2 *Experimental results*

The relative strip displacements measured during the simulation of the asphalt scenario for test No.3 are represented in Figure 7. The coordinate value *x*=0 mm corresponds to the end of the bond length where the prestress force was released while the coordinate value *x*=300 mm is related to the other strip end. In spite of no failure was observed during the simulation of the asphalt scenario, experimental results showed a deformation of the strip and a decrease of the prestress force due to the creep deformation of the epoxy adhesive at elevated temperatures. After the simulation of the asphalt scenario the strip displacements remained approximately constant. The maximum slip displacements in the strip were measured in the zone of the bond length where the shear stress level was the highest, namely, near the zone where the prestress force was released (*x*=0 mm).

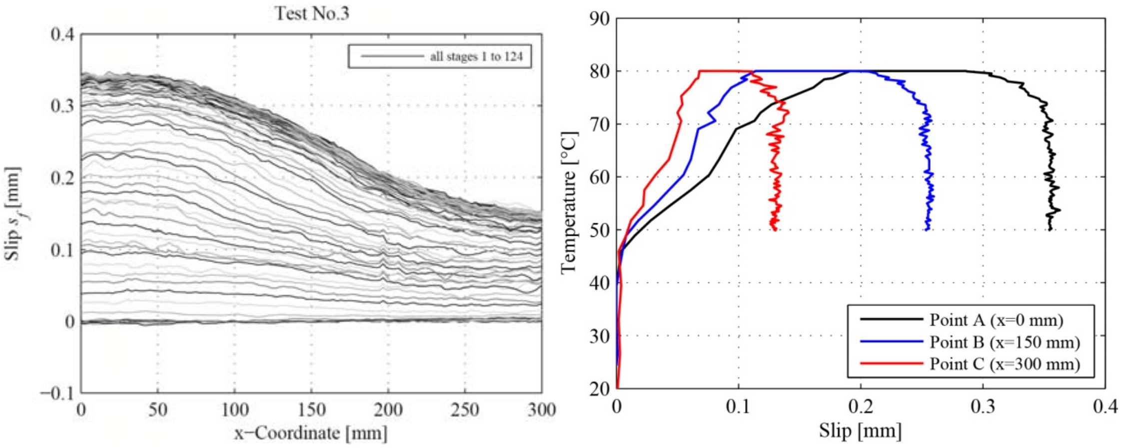

Figure 7. Simulation of the asphalt scenario for Test No.3: (Left) Slip distribution measured in the strip being each line related to a different temperature level; (Right) Evolution of the strip slip at three different points.

According to Figure 7 when the epoxy temperature exceeds the glass transition temperature a redistribution of the initial shear stress state in the epoxy layer starts. In this manner part of shear stresses that initially are resisted in the more loaded end of the bond length are transferred to the other side of the strip where the initial shear stress level is lower. Since the beginning of the cooling down a uniform longitudinal strip displacement was measured. According to this fact, it is possible to assume that at the end of the test a constant shear stress state is reached in the epoxy layer.

3.3 *Influence of the epoxy elastic modulus value in the joint stress state*

The behaviour of a gradient anchorage subjected to a high temperature scenario is governed by the epoxy properties at this temperature level. At elevated temperatures epoxy adhesives are mainly characterized by the significant decrease of the elastic modulus (Michels et al. (2015)). In this section the stress state of a gradient anchorage is studied as a function of the epoxy elastic modulus value.

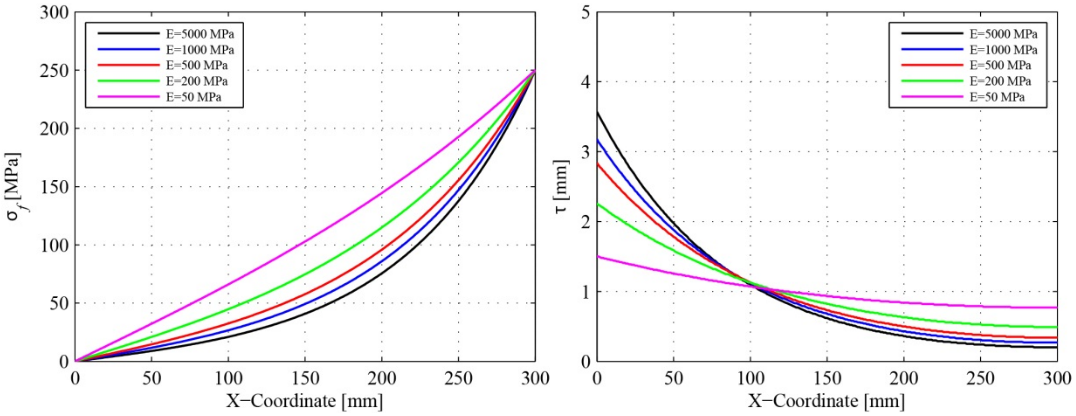

Figure 8. Stress state after the releasing stage for different epoxy temperature levels: (Left) Tensile stresses in the strip; (Right) Shear stresses in the strip/epoxy/concrete joint.

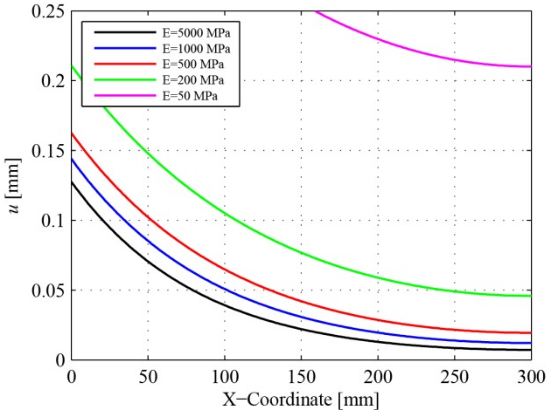

Figure 9. Strip displacements after the releasing stage for different epoxy temperature levels.

A parametric study of the joint stress state through the analytical model proposed in this paper is presented in Figure 8 and Figure 9. Figure 8 shows the variation of the strip tensile stress and shear stresses along the bond length for different epoxy elastic modulus values. Each elastic modulus is related to a different epoxy temperature. According to the graphs low epoxy temperature levels related to epoxy adhesives with high elastic modulus present a high shear stress concentration in the area where the prestress force is released. Results show that when the epoxy elastic modulus decreases due to an elevated temperature scenario the longitudinal displacements in the strip increase significantly.

As Figure 8(Right) shows, sections near to the strip end where the force is released have a decrease of the shear stress level due to the softer behaviour of the epoxy adhesive. A schematic representation of the shear stresses in the bond length during the simulation of an asphalt scenario is represented in Figure 10 where the left curve is related to the end where the prestress force is released (x=0mm) and the right curve to the other strip end (x=300mm). During the simulation of the asphalt scenario the side of the bond length subjected at the beginning of the test to a low shear stress level increases its load level due to the redistribution of the shear stresses. According to Figure 8(Right), it is possible to assume that when the maximum epoxy temperature is reached the shear stress distribution along the bond length is approximately constant.

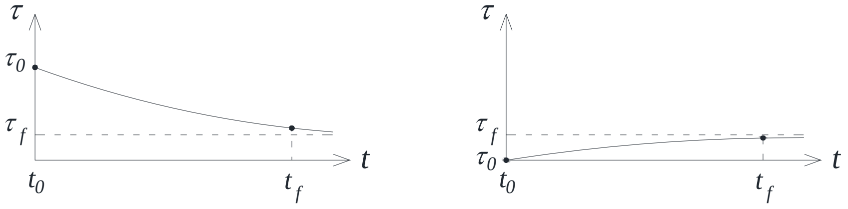

Figure 10. Evolution in time of the shear stress state in the joint during the simulation of an asphalt scenario: (Left) Section located close to the end where the prestressed force is released (x=0 mm); (Right) Section located close to the other end of the strip (x=300 mm).

For a given x-coordinate value the relative displacement of the strip (u) during the simulation of an asphalt scenario can be obtained according to eq.(14) where u_{el} and u_{creep} are the elastic and the creep displacements of the epoxy adhesive respectively.

$$u = u_{el} + u_{creep} \tag{14}$$

The elastic displacement (u_{el}) can be estimated through eq.(15) being τ_0 the initial shear stress at the beginning of the test for each x-coordinate value.

$$u_{el} = \frac{\tau_0}{K_{el}} \tag{15}$$

Theoretical and experimental studies have been done so far concerning creep behavior of concrete under a time dependent load (Ghali et al. (2002)). Following the same methodology employed for concrete, the creep deformation at time t of an epoxy adhesive subjected to a variable load can be evaluated through eq.(16) where $\varphi(t,t_0)$ and $\chi(t,t_0)$ are the creep and aging coefficients respectively for a load applied at time t_0.

$$u_{creep} = \varphi(t,t_0)\frac{\tau_0}{K_{el}} + \chi(t,t_0)\varphi(t,t_0)\frac{\tau_f - \tau_0}{K_{el}} \tag{16}$$

Substituting eq.(15) and eq.(16) in eq.(14), eq.(17) is obtained. According to this expression two effects are considered during the simulation of an asphalt scenario. On the one hand, there is an important elastic deformation due to the decrease of the epoxy elastic modulus at elevated temperatures. On the other hand, creep deformation of the epoxy adhesive plays also an important role for such critical scenarios. More tests in epoxy specimens are necessary in order to define more accurate values for the aging and creep coefficients of this material at different temperature levels.

$$u = \frac{\tau_0}{K_{el}} + \varphi(t,t_0)\frac{\tau_0}{K_{el}} + \chi(t,t_0)\varphi(t,t_0)\frac{\tau_f - \tau_0}{K_{el}} \tag{17}$$

4 CONCLUSIONS

Some conclusions have been obtained from the experimental and analytical study presented in this paper:

- The stress state of a gradient anchorage has been studied in the paper through an analytical model. The developed model predicts with good accuracy the experimental results.
- The application of the asphalt layer at the top side of a reinforced concrete bridge strengthened with prestressed EB CFRP strips could influence the long-term behavior of such reinforcements.
- Experimental results showed that during the simulation of high temperature scenario there is an important deformation of the strip/epoxy/concrete joint mainly due to the decrease of the epoxy elastic modulus and the creep deformation of the epoxy adhesive.
- The relative strip displacements during a high temperature scenario can be calculated through the sum of an elastic deformation and a creep deformation of the epoxy adhesive layer.
- A theoretical expression has been proposed in the paper to study the creep behavior of the epoxy adhesive under a time dependent load in to consider the shear stress redistribution in the strip/epoxy/concrete joint.

5 REFERENCES

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