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Thermal modeling for the prediction of the epoxy adhesive service temperature used in CFRP strengthening of RC bridges

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ABSTRACT: The mechanical response of Carbon Fiber Reinforced Polymer (CFRP) used for the strengthening of reinforced concrete bridges is particularly influenced by the temperature. The epoxy-based adhesives used to bond CFRP to concrete are characterized by the glass transition temperature (T_g), which conventionally marks the transition between the glassy state and the rubbery state (visco-elastic state). To avoid the risk of extensive creep and damages (premature debonding), the service temperature (T_s) should be kept between 10 to 15° C lower than the T_g.

The present study focuses on the determination of the temperature that can occur in the adhesive when CFRP strips are applied to strengthen the top surface of RC bridges. Ongoing experimental tests, which simulate a strengthened lateral cantilever of a RC box girder bridge show, that a service temperature of approximately 40-50°C is likely to be encountered in the adhesive during hot summer days in Dübendorf (near to Zurich, CH); the indicated temperature range depends on the thickness of the asphalt layer. These temperatures are comparable to the T_g values of commercially available adhesives (50-60°C), therefore for this type of applications, an epoxy adhesive with higher T_g is recommended.

A numerical model was developed to predict the temperature of the epoxy adhesive under the asphalt layer. This model is able to take into account the solar radiation and the daily change of air temperature during summer hot days. The numerical model was validated against the experimental results. Finally, a parametric analysis was carried out to analyze how geometry and environmental conditions can affect the adhesive temperature.

1 INTRODUCTION

Carbon Fiber Reinforced Polymers (CFRP) are frequently used to strengthened reinforced concrete (RC) bridges and structures; their resistance to corrosion allows their application on the external surface of the RC element, without any (or very few) protection. However, CFRP effectiveness typically relies on the mechanical properties of epoxy-based adhesives. Thus, it is important to know the operating temperature in the adhesive layer. It is known that the adhesive reduces its stiffness and maximum shear strength when exposed to high temperatures (Klamer et al. 2006, Leone et al. 2009, Firmo et al. 2015). Thus, the bond between concrete and FRP is considerably affected. The critical temperature at which the structural adhesive loses its mechanical strength is indicated as the glass transition temperature (T_g) (Figure 1a). As highlighted in (Michels et al. 2015) the definition of glass transition is not trivial because the different norms do not agree on the definition of T_g, furthermore, the value of T_g is not constant, it depends on the curing temperature and increases in time. As a result and in order to avoid the risk of damages (e.g. premature debonding) and extensive creep, the design guidelines (e.g. ACI) recommend that the service temperature should be kept 10-15 °C lower than the T_g. Particularly in cases of moderate sustained loads, is crucial to evaluate the operating temperature, because the creep in the adhesive increases with the temperature; this highlights the importance of guarantee an operational temperature range possibly far from the value of T_g (Figure 1a). The T_g of commercially available structural adhesives for FRP applications is estimated between 50-60°C, which does not represent any issues for standard building application. Nevertheless, when CFRP is bonded to civil structures exposed to elevated ambient temperature and solar radiation, these T_g values might be considered relatively low if compared to the maximum achievable temperature in the adhesive.

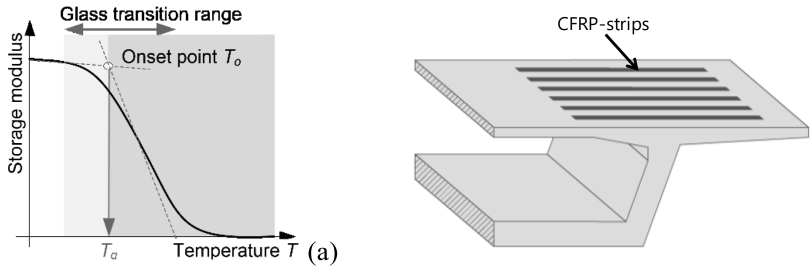

Figure 1. (a) Schematic representation of the elastic modulus of an epoxy-based adhesive as a function of the temperature, (b) Graphical representation of the lateral cantilever strengthening of a hollow-box girder bridge.

In a recent project (Czaderski et al. 2017), focused on the flexural strengthening of a lateral cantilever of hollow box girder bridges (Figure 1b), experimental tests were performed to evaluate the maximum achievable temperature in the adhesive during the mastic asphalt application and the fatigue behavior at elevated temperature (Gallego et al. 2018). Results showed that a good performance in case of unstressed CFRP strip. The present project is an extension of the aforementioned experimental program and focuses on the assessment of the service life of the CFRP strengthened structures under the effects of sustained load and exposure to external environment over several years.
This paper presents a numerical model, calibrated on experimental long-term tests, capable of estimating the adhesive temperature in a strengthened RC slab, considering the effects of daily temperature and solar radiation fluctuation. A parametric study has been performed to study how the temperature of the adhesive is affected by the thickness of the slab and asphalt layer. The numerical model is then used to evaluate the temperature in the adhesive of a strengthened concrete slab hypothetically located in Sion, Valais (CH), where the highest temperatures (with respect to Swiss climate) are recorded.

2 EXPERIMENTAL TESTS

2.1 RC strengthened slab-strips with an asphalt layer and sustained load

The ongoing experimental program was designed to simulate a strengthening intervention on a lateral cantilever of a hollow box girder bridge (Figure 1b). For this purpose, two one-way RC slabs of 5000x1000x220 mm^3 were studied. Both slabs were strengthened with two unstressed CFRP strips of length, width and thickness equal to 5000mm, 100 mm and 1.2 mm, respectively. The long-term experimental set-up was installed in 2015 at Empa (Dübendorf, Canton Zürich – CH) and is shown in Figure 2a; the slab specimens are supported at their center and restrained by bilateral support at the left end. Both specimens were exposed to the external environment and were loaded with 14.8kN acting on the free end. The CFRP strips

were bonded to the slab top surface, with a layer thickness of approx. 2 mm. A mastic asphalt layer of 80 mm inclusive of waterproofing membrane (polymer bitumen layer) was applied following the current common practice in Canton Zürich. The final pavement build-up is shown in figure 2b.
It is then underlined that both slab specimens have equal geometry and strengthening configuration. The only differences are in the CFRP and adhesive products, which were provided by two different companies: S&P Clever Reinforcement Company AG and SIKA AG both from Switzerland. The tested T_g, following the ASTM E1640 (2013), after 28 days at room temperature condition, is approx. 45 °C for both and S&P Resin 220 and Sikadur 30 adhesives (Michels et al. 2015).

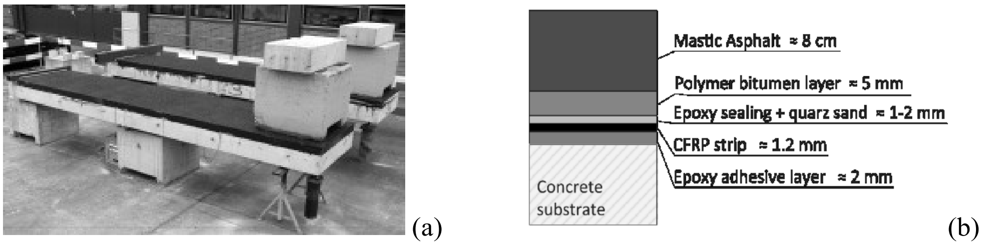

Figure 2. (a) Long-term experimental set-up, simulating a CFRP strengthened lateral cantilever, (b) pavement detailing build-up in presence of CFRP strengthening (drawing not in scale)

2.2 Monitoring system

The environmental parameters (such as air temperature and humidity), and the temperature in the adhesive layer and in the asphalt were monitored using a wireless monitoring system. Two thermocouples were installed in the adhesive layer and one in the asphalt layer of each slab specimen. The latter was installed at approximately 20 mm from the top surface.

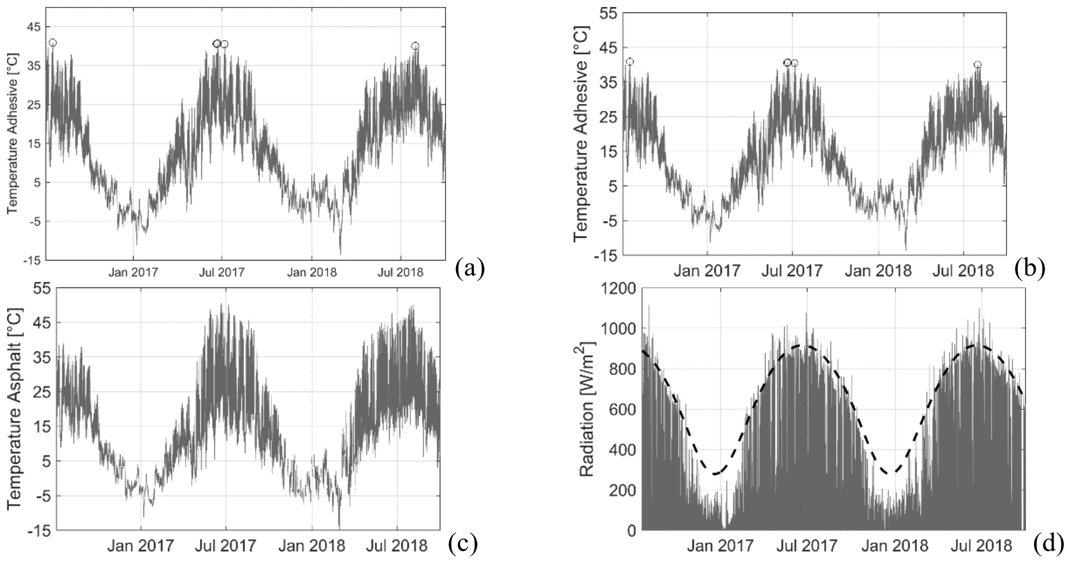

Figure 3. Temperature and radiation measurements, (a) Air temperature, (b) Average temperature in the epoxy adhesive, (c) Average temperature in the Asphalt (d) Solar radiation.

The solar radiation was measured by using two silicon-cell-pyranometers. The missing measurements required as input for the numerical modeling as the wind speed was integrated using the MeteoSwiss base level monitoring networks (station: Dübendorf-Giessen). Figure 3a shows the values of the air temperature starting from fall 2015. In the Figure, the days where the maximum temperature exceeded 35°C are highlighted using a circle marker, evidencing the presence of hot days also in the north of Switzerland. Figure 3b and 3c show the seasonal fluctuation of the epoxy adhesive and asphalt measured temperatures. It can be noticed that during the recorded timespan, the temperature in the adhesive exceeded 40°C twice in a year, meanwhile, the asphalt easily reaches higher temperatures with a maximum around 50°C. The test setup also comprises a third slab strengthened with prestressed CFRP strips, which has a thin layer of protective paint instead of an asphalt layer. A temperature of 50 °C is achieved in the adhesive in this test configuration, however, only the specimens with asphalt layer are considered in this study, because of more interest for the practical bridge applications. Finally, Figure 3d shows the solar radiation measured by two silicon-cell pyranometers. In the figure, the daily maximum radiation calculated according to the Daneshyar–Paltridge–Proctor clear sky model (Reno et al. 2012) is also plotted using a dashed line. In winter, the solar radiation was typically very low, because of the cloudy sky, but also because of shading effects induced by the surrounding buildings.

3 NUMERICAL MODEL

3.1 Modeling approach

The transient thermal problem is studied by means of finite element (FE), the developed FE model is implemented in the Comsol Multiphysics software (v 5.3a). The simulated 3-dimensional volume, representing only a section of the RC slab, is 1000 x 300 x 200 mm^3. This simplified approach was adopted to save computational time, after verifying to be effective when compared to the full slab model. The model description, based on the heat transfer equation (Eq.1) was previously presented in a preliminary numerical study by Breveglieri et al (2018):

$$\rho C_P \frac{\partial T}{\partial t} + \nabla \mathrm{q} = 0,\ with\ q = -k\nabla T. \tag{1}$$

The first term of Eq.1 represents the change of internal energy (ρ, is the density of the material and C_p, the heat capacity) meanwhile the second term, by means of the Fourier's law, serves to define the conductive heat flux q (k, is the thermal conductivity). The initial, and external boundary condition are expressed by Eq. (2) and Eq. (3):

$$T = T_0 \tag{2}$$

$$-k\frac{\partial T}{\partial n} + q_c + q_r = 0 \tag{3}$$

where T_0 is the initial temperature, and q_c and q_r stand for the heat transfer contribution at the boundary attributable to convective heat flux and radiation, which is described with Eqs. (4) and (5), respectively.

$$q_c = h(T_{ext} - T) \tag{4}$$

T_{ext} is the extremal temperature which is assumed to be varying during the day and h represents the convection-heat transfer coefficient. The software allows to considerer radiative boundary condition for different wavelengths, as for example the solar (short-wave radiation λ_1<2.5μm) and ambient (long-wave radiation λ_2> 2.5μm). Eq. (5) express the radiative boundary condition.

$$q_r = \sum_{i=1}^{2} \varepsilon_{\lambda i}\big(G_{\lambda i} - e_{b,\lambda i}(T) \cdot FEP_{\lambda i}(T)\big) \tag{5}$$

For each i[th] wavelength, in Eq. (5): $\varepsilon_{\lambda i}$ is the emissivity , $G_{\lambda i}$ is the incoming radiation, $e_{b,\lambda i}(T)$ is the power radiated according to the Stefan-Boltzmann law and $FEP_{\lambda i}(T)$ is the fractional emissive power. The incoming radiation $G_{\lambda i}$, is calculated taking into account both the solar $G_{\lambda i.ext}$ and the ambient, $G_{\lambda i,amb}$, irradiances shown in Eq. (6). The $G_{\lambda i.amb}$ is calculated similarly to the last term of Eq. (5), where temperature value needs to be assumed as T_{ext}. The solar irradiance, $G_{\lambda i.ext}$, is a function of position of the sun (zenith angle θ) with respect to studied location and the value of the clear sky noon normal irradiance (Eq.7). The value of I_s, takes into account both diffuse and beam radiation.

$$G_{\lambda i} = G_{\lambda i,amb} + G_{\lambda i.ext} \tag{6}$$

$$G_{G_{\lambda i.ext}} = I_s \cdot cos\theta \tag{7}$$

3.2 Model input

3.2.1 Material parameters

The material parameters using in the numerical simulation were chosen from the literature on bridge thermal stresses and deformation (Lichte, 2004, Sannio, 2017) and from studies on the influence of the temperature of strengthened structures using CFRP composites (Taillade et al. 2012). In order to improve the quality of the simulations, tests on a similar slab heated artificially in laboratory condition are currently being performed. The used material parameters in the presented simulations are presented in Table 1.

Table 1. Material Parameters

Material	ρ [kg/m^3]	C_p [J/(kg K)]	k [W/(m K)]	ε_S[-]	ε_L[-]
Concrete	2400	950	0.16	0.6	0.90
Asphalt	2250	920	0.85	0.9	0.88
CFRP	1600	880	0.5	--	--
Adhesive	1750	1200	0.2	--	--

Notations: ρ - Density, C_p – Heat capacity, k- Thermal conductivity, ε_S – Emissivity in short wavelength, ε_L – Emissivity in long wavelength.

The values of epoxy-based adhesive and CFRP laminates even after a detailed check of the available literature review are difficult to estimate, however, due to the small thickness and as a consequence almost negligible mass they don't affect significantly the results. The epoxy-based adhesive is typically characterized by a low coefficient of thermal conductivity. The CFRP property depends on the percentage of fiber content, and on the direction of the heat flux since laminates have a strong orthotropic thermal behavior. In the orthogonal direction to the fiber, the thermal conductivity k is usually close to the value that characterizes the FRP matrix. Since the waterproof membrane is a bitumen-based material (similar to the asphalt layer), it has not been introduced in the numerical model, at the present stage of the research.

3.2.2 Environmental input

From Figure 3, it is possible to observe that during the monitoring time, two "hot timeframe" occurred. During these periods, the maximum daily temperature was significantly over the average summer temperature for several days. For concrete bridges design, the maximum temperatures are likely to be achieved after a sequence of hot days. Also in the case of an epoxy adhesive, the maximum values of high temperature were observed during this so-called "heat wave". The first wave took place indicatively from 21.06.2017 to the 26.06.2017 and the second

form the 29.07.2018 to 06.08.2018. In the present work, only the results obtained from the simulation of the first timespan are presented.
The environmental input to the model consists of the air temperature, the value of solar radiation and the wind speed. The first two variables were measured by the monitoring stations, with a time resolution of 10 minutes, meanwhile, the wind data were obtained from average hourly aggregated data measured from the Dübendorf-Gissen MeteoSwiss station. The wind (v) speed is used to calculate the value of heat transfer coefficient h presented in Eq. (8). The value of h has been assumed equal to the empirical formula proposed by Kuchling (1996):

$$h = 5{,}4 + 4{,}5 \cdot v \quad \text{if} \quad v < 5\ \text{m/s}^2$$
$$h = 7.52 \cdot v^{0.78} \quad \text{if} \quad v \geq 5\ \text{m/s}^2 \qquad (8)$$

4 RESULTS

Figure 4 compares the results of the numerical model with the experimental data. The mean measured value, considering the standard deviation, is shown for the adhesive (Figure 4a) while the two thermocouples measurements are shown for the asphalt (Figure 4b). It is visible in the figures, that the model is able to determine with good accuracy the maximum temperature and the daily fluctuation in the adhesive. The 22nd June 2017, the average adhesive reached its maximum temperature of 40.5°C, whereas on the same day the maximum air temperature was 36.4 °C. The temperature obtained from the FE model is 41.34 °C. Similar results are obtained for the asphalt temperature, which exceeded 50 °C. High temperatures in the adhesive occur after a sequence of hot days and intense solar radiation. The presence of wind is also significant since it affects heat exchange due to convection at the external surfaces.

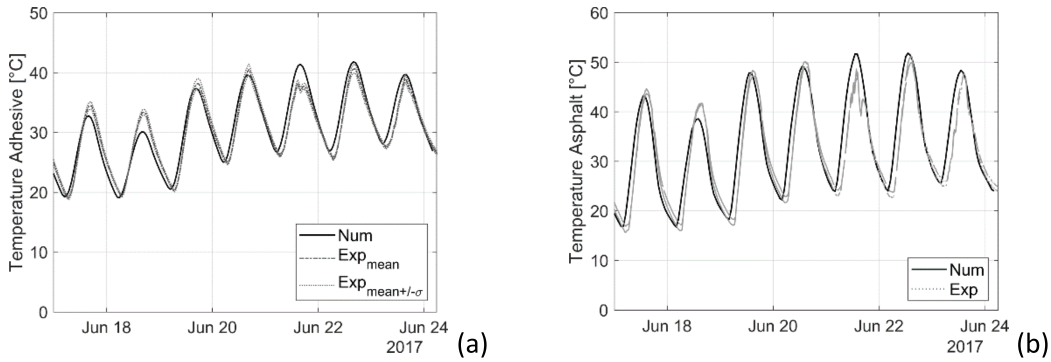

Figure 4. Temperature development over the simulated timespan during a heat wave, comparison with the experimental results (a) adhesive (b) asphalt.

5 PARAMETRIC STUDY

5.1 Influence of slab and asphalt layer thickness on the adhesive temperature

A parametric study using the same parameters as used in Figure 4 explores how the thickness of the concrete slab and the asphalt layer can influence the results. The importance of the asphalt layer thickness is known however, it is not considered in the Swiss code (SIA 261). Figure 5a shows how the temperature in the adhesive changes when three different values of asphalt thickness (t_{asph}: 50, 80, 120 mm) covering a 220 thick concrete slab are chosen. The results show the positive effect of a thicker layer of asphalt. For the smallest value of t_{asph}, the temperature can rise up to 44.3 °C, while it drops to 38.2 °C for a t_{asph} equal to 120mm. The thickness of the RC slab, t_{slab}, has a minor influence when compared to the t_{Asph}. Figure 5b shows, for a 50 mm thick asphalt layer, that higher adhesive temperatures can occur in thicker slabs. It is possible to state that the worst condition takes place for a thin asphalt layer and thick concrete slab. As a result, an adhesive temperature of 46.2°C was calculated for t_{Asph} and t_{slab} equal to 50 and 500 mm, respectively.

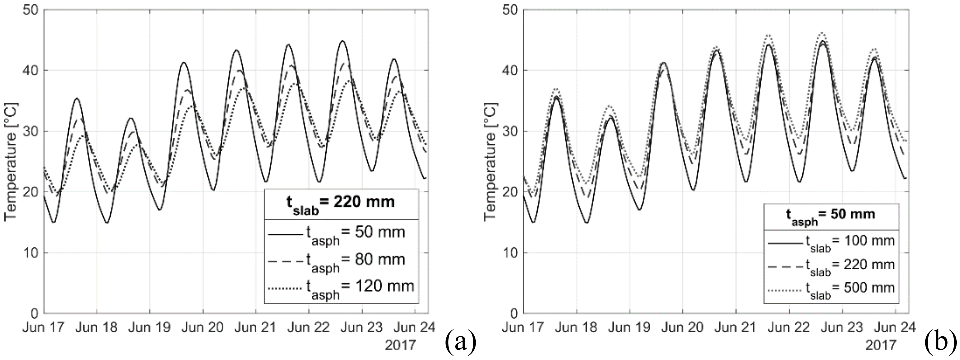

Figure 5. Influence of geometrical thickness (a) asphalt and (b) slab on the adhesive temperature.

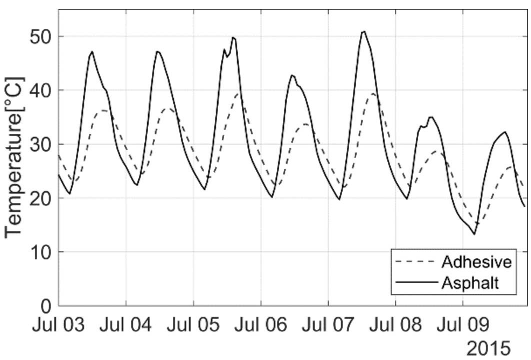

Figure 6. Simulation results of the tested slab when located in Sion.

5.2 Alternative location: Sion, Valais (CH)

One of the aims of the project is to investigate if within the Swiss territory elevated summer temperatures together with intense solar radiation can represent an issue for bridge decks strengthened using CFRP, due to the high temperature that can be reached in the adhesive. Sion in canton Valais (CH) is one of the cities in densely populated areas with the highest summer temperatures recorded in Switzerland. From the temperature records, the highest hourly average temperature (37.4 °C) was measured on the 7th of July 2015. A numerical simulation of a slab presented in the previous sections has been carried out by assuming environmental parameters as the one recorded from the meteorological station located in Sion. The days between the 2nd July to the 7th of July 2015 have been simulated and the results are presented in Figure 6. The temperatures in the adhesive and in the asphalt achieved a maximum of 39.2 and 50.4 °C, respectively. The calculated values are comparable to the measurements carried out in Dübendorf. The effects of the higher value of air temperature in Sion are probably attenuated by the higher wind activity. In terms of solar radiation, there is a small difference between Dübendorf and Sion, nevertheless, Switzerland is a small country and the value solar radiation can be assumed constant over the entire country for such type of simulations.

6 CONCLUSIONS

The present work presents a numerical model developed to estimate the service temperature in the adhesive used to bond CFRP to the top surfaces of RC bridges. The study focuses on the Swiss climate and analyses the effects of solar radiation and elevated ambient temperatures. The results

obtained from the FE model, in agreement with the experimental evidence, showed that during a sequence of hot summer days, temperatures close to T_g can be achieved. The mechanical tests on the slab specimens, planned by the end of summer 2019 are essential to draw the appropriate conclusions.
Nevertheless, the present work showed that the experimental setup in Dübendorf (near to Zürich) could be considered as representative for the Swiss climate since the simulation in the alternative location of Sion provided similar results. Additional environmental scenarios need to be evaluated to confirm these findings.
It was demonstrated that higher temperatures near 50 °C can be achieved for a thinner layer of asphalt and thicker slabs. This result remarks that it is not possible to assure a service temperature in the adhesive, 10 to 15 °C lower than the T_g, reported in the technical data sheets.
At the present stage of the research, an adhesive with a higher value of Tg is recommended. As an alternative, strategies to reduce the temperature in the adhesive, which comprise of the introduction of an insulating layer or the use of a mastic asphalt with low emissivity needs to be implemented.

7 ACKNOWLEDGMENTS

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8 REFERENCES

Breveglieri, M., Weber, B. and Czaderski, C. Solar Radiation Effects on the Epoxy Adhesive Temperature Used to Bond CFRP to Concrete Beams. Comsol Conference Lausanne (2018).

Czaderski, C., Gallego, J. and Michels, J. Temperature stability and durability of Externally Bonded CFRP strip in bridge construction. Forschungsprojeckt ABG 2012/001 (2017) http://www.mobilityplatform.ch

Firmo, J.P., Correia, J.R., Pitta, D.,Tiago, C. and Arruda, M.R.T. Experimental characterization of the bond between externally bonded reinforcement (EBR) CFRP strips and concrete at elevated temperatures. Cement and Concrete Composites, 60, 44-54 (2015).

Gallego, J.M., C. Czaderski, M. Breveglieri, and J. Michels, Fatigue behaviour at elevated temperature of RC slabs strengthened with EB CFRP strips. Composites Part B: Engineering, 2018. 141: p. 37-49.

Klamer, E.L., Hordijk D.A., and Kleinman, C.S. Debonding of CFRP laminates externally bonded to concrete specimens at low and high temperatures, Third International Conference on FRP Composites in Civil Engineering (CICE). 2006. p. 35-38.

Kuchling, H. Taschenbuch der Physik. Mit Tabellen. 16. Aufl. Leipzig: Fachbuchverl. im Carl Hanser Verlag (1996).

Leone, M., Matthys, M., Aiello, M.A., Effect of elevated service temperature on bond between FRP EBR systems and concrete. Composites Part B: Engineering, 40, 85-93, (2009)

Lichte, U. Klimatische Temperatureinwirkungen und Kombinationsregeln bei Brückenbauwerken. Universität der Bundeswehr München, Institut für Konstruktiven Ingenieurbau,PhD Thesis, (2004).

Michels, J., Widmann, R., Czaderski, C., Allahvirdizadeh, R. and Motavalli, M. Glass transition evaluation of commercially available epoxy resins used for civil engineering applications. Composites Part B: Engineering, 77, 484-493, (2015).

Sannio, D. Genauigkeit monitoringbasierter Lebensdauerprognosen von Betonbrücken bei Spannstahlermüdung, Schriftenreihe des Instituts für Konstruktiven Ingenieurbau¸ Ruhr-Universität Bochum (2017).

SIA 261 – Einwirkungen auf Tragwerke, Schweizerischer Ingenieur- and Architektenverein (2014).

Taillade, F., Quiertant, M., Benzarti, K. and Aubagnac, C. Shearography and pulsed stimulated infrared thermography applied to a nondestructive evaluation of FRP strengthening systems bonded on concrete structures. Construction and Building Materials, 25, 568-574, (2011).