Adhesively Bonded CFRP Composites for Steel Strengthening: An overview

Elyas GHAFOORI [1], QianQian YU [2], Reza HAGHANI [3], Ardalan HOSSEINI [1,4], Ali HADIGHEH [5], Xianglin GU [2], Masoud MOTAVALLI [1], Xiaoling ZHAO [6]

[1] Structural Engineering Research Laboratory, Swiss Federal Laboratories for Materials Science and Technology (Empa), Duebendorf, Switzerland.
[2] Key Laboratory of Performance Evolution and Control for Engineering Structures of Ministry of Education, Tongji University, Shanghai, China.
[3] Division of Structural Engineering, Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden.

[4] Resilient Steel Structures Laboratory, Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland.

[5] School of Civil Engineering, University of Sydney, Sydney, Australia.

[6] Department of Civil and Environmental Engineering, University of New South Wales (UNSW), Sydney, Australia.

Contact e-mail: elyas.ghafoori@empa.ch

ABSTRACT: Adhesively bonded joints are commonly used for carbon-fibre reinforced polymer (CFRP) strengthening of concrete structures. There are a relatively large number of studies on different aspects of the CFRP-to-concrete bonded joints, however, this is not the case for bonded joints used for the strengthening of steel structures. Long-term performance and uncertainty related to environmental durability are critical barriers for the wide applications of bonded joints in structural applications. Moisture and temperature and their combined effect on both constituent material and system levels are identified as the most critical environmental factors. There is a need for studies that address short- and long-term structural behavior of the CFRP-to-steel bonded joints. This study aims to provide a review on the most recent works on the CFRP-to-steel bonded joints conducted by different active research groups in Switzerland, China, Sweden and Australia. Finally, some recommendations for future studies in this topic will be provided.

1 INTRODUCTION

Carbon-fibre reinforced polymer (CFRP) materials are composites with high strength to weight ratio, non-corrosive and have a superior fatigue performance (Zhao, 2013), which make them suitable for strengthening of steel bridges, (e.g., (Hosseini et al., 2019a, Ghafoori et al., 2018, Ghafoori et al., 2015b)). This work will summarize the most recent studies that have investigated the bond behavior between CFRP and steel substrates (by different active research groups worldwide). The short- and long-term behavior of the CFRP-to-steel bonded joints will be addresses.

This study starts with presenting recent research results on CFRP-to-steel interfacial bond behaviour. It continues with presenting the results of a series of tests on environmental durability of adhesive bonds between steel and CFRP with a focus on hygrothermal effects. Next, the applicability of a new strengthening technique that includes a vacuum resin infusion and heating process for strengthening of steel structures is discussed. Furthermore, the results of a series of tests for development of a prestressed bonded retrofit system are presented. Finally, the application of bonded CFRP composites for strengthening of an old historic Australian bridge is explained. At the end, a list of suggestions for future studies on this topic is provided.

2 CFRP-TO-STEEL INTERFACIAL BOND BEHAVIOUR

CFRP-to-steel interfacial behavior is a major concern in a retrofitting scheme that relies on load transfer between CFRP and steel. Extensive experimental studies have been performed and several bond strength prediction models have been already proposed (Hart-Smith, 1973, Xia and Teng, 2005, Yu et al., 2012). Consequently, the reliability based design for externally-bonded CFRP strengthening could be performed based on these models. When aiming at a certain reliability index, a resistance factor for structural action is normally introduced. It was demonstrated that the resistance factor is highly depended on the uncertainty of each model (Zhang et al., 2018).

A database composed of 400 single/double-lap shear joints (Yu et al., 2018) was collected to characterize the model uncertainty of the frequently used Hart-Smith model (Eq. 1)

$$P_{ult} = b_p \min\left\{ \sqrt{2\tau_f t_a\left(\frac{1}{2}\gamma_e+\gamma_p\right)2E_s t_s\left(1+\frac{E_s t_s}{2E_p t_p}\right)}, \sqrt{2\tau_f t_a\left(\frac{1}{2}\gamma_e+\gamma_p\right)4E_p t_p\left(1+\frac{2E_p t_p}{E_s t_s}\right)} \right\} \;(L \geq L_e) \quad (1a)$$

$$P_{ult} = P_{ult} L / L_e \;\; (L < L_e) \quad (1b)$$

$$L_e = \frac{P_{ult}}{2\tau_f b_p} + \frac{2}{\lambda}, \;\; \lambda = \sqrt{\frac{G_a}{t_a}\left(\frac{1}{E_p t_p} + \frac{2}{E_s t_s}\right)} \quad (1c)$$

where P_{ult} is the ultimate tensile strength, L is the bond length, L_e is the effective bond length, τ_f is the bond strength taken as $0.8f_{t,a}$ (Xia and Teng, 2005), $f_{t,a}$ is the adhesive tensile strength, γ_e and γ_p are the adhesive elastic and plastic shear strains, respectively, E, t, and b denote the elastic modulus, thickness and width, respectively, subscripts p, a, and s represent CFRP, structural adhesive and steel substrate, respectively, G_a is the shear modulus of the adhesive.

A model factor ε defined as the ratio of an experimental result P_m to the corresponding predicted value P_c was adopted to investigate the model uncertainty. Figure 1.a plots the statistics results, where the average value of 1.60 indicated a conservative prediction and the coefficient of variation (COV) above 0.4 was much larger than the commonly accepted value ranging from 0.2 to 0.3. A preliminary study on the systematic reason causing the large COV (Yu et al., 2018) demonstrated that the high COV was not random, but heavily dependent on the input parameters. Figure 2.a gives a typical example of ε against $f_{t,a}$, which clearly indicated the nonlinear negative correlation. Therefore, an equation f was introduced to filter the systematic correlation. Among the database, 315 data points were selected to develop the expression f, and the remaining sets were used to verify the performance of the residual model factor ε^*.

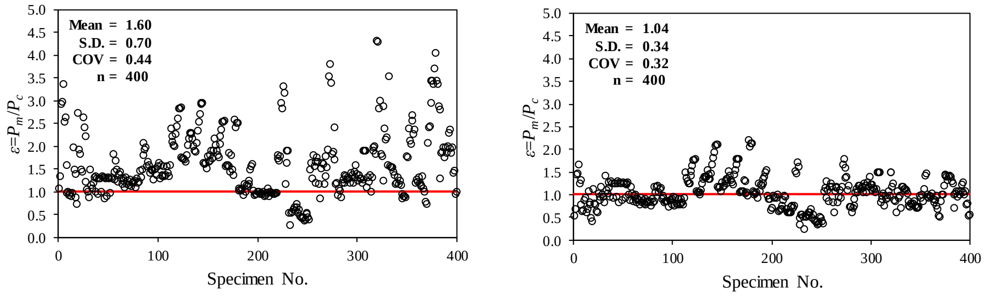
Since there were more than one case for a certain input parameter as shown in Figure 2.a, the multiple model factors were treated by an averaging process and are illustrated by hollow dots in Figure 2.b. Afterwards, the variation was fitted by a power function as follows

$$\varepsilon_{ave} \propto B_1 f_{t,a}^{A_1} \quad (2)$$

where A_1 and B_1 are the coefficients of the best fitted power curve. The core functions for other parameters were deduced in a similar way and the parameters were determined through multiple linear regression. Eventually, Eq. (3) was adopted to describe the systematic variation of ε

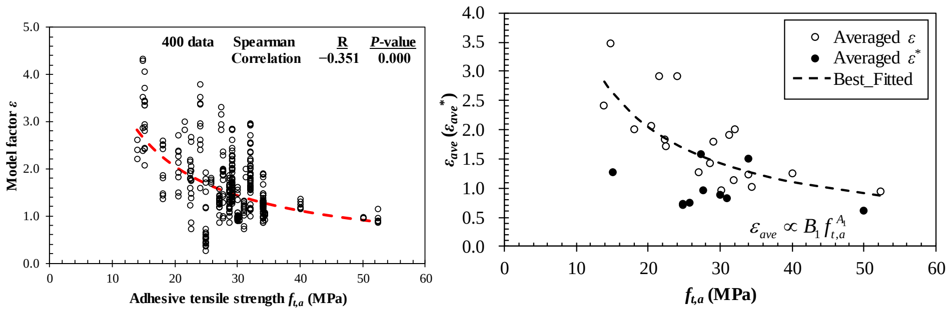
$$\varepsilon = e^{-0.937} \times e^{-0.454\ln f_{t,a}} \times e^{0.291/\nu_a} \times e^{-0.013t_s} \times e^{0.487\ln b_s} \times e^{276.83/(E_a t_a)} \times e^{-17.456/(E_p t_p)} \times \varepsilon^* \qquad (3)$$

The averaged residual model factors of the verification sets are depicted by solid dots in Figure 2.b, which randomly distributed around 1.0. It was therefore implied that the dependency of the model factor has been largely decreased. The distribution of the model factor after modification shown in Figure 1.b exhibits a mean value of 1.04 and a COV value of 0.32, which demonstrated an improved accuracy of the perdition model.



(a) Before modification (b) After modification

Figure 1. Model uncertainties for Hart-Smith model (a) before and (b) after modification.



(a) (b)

Figure 2. Variation of model factor (a) with adhesive tensile strength for Hart-Smith Model, and (b) after averaging process.

3 ENVIRONMENTAL DURABILITY OF ADHESIVE BONDS BETWEEN STEEL AND CFRP

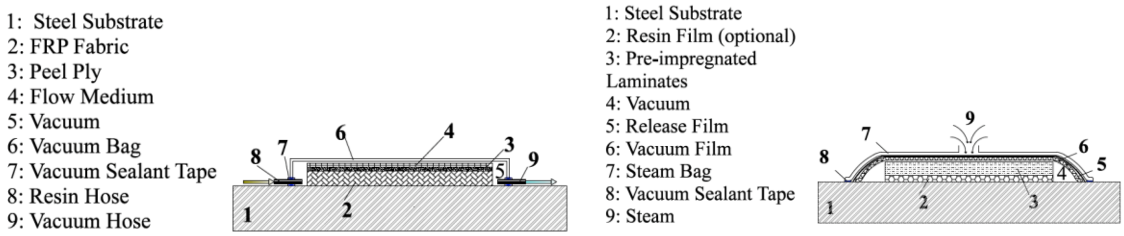
Despite numerous studies that address the short-term behavior of adhesively bonded CFRP-to-steel bonded joints, uncertainty with respect to long-term performance still remains. This knowledge gap is regarded as a critical barrier, hindering the widespread application of FRPs to strengthen and retrofit steel structures. Adhesive bonding introduces an inevitable yet crucial weak link between the composite element and steel member (da Silva et al., 2011). In other words, the effectiveness of the joint is dependent on the quality, integrity and durability of the adhesive bond between the adherends. Given the aggressive environments, to which these adhesively bonded joints are generally subjected, durability issues take on the utmost significance. Concerns about the environmental durability of adhesively bonded joints have been reflected in recent research publications, in which the key areas of interest have been mainly to understand the underlying mechanisms of degradation (Venables, 1984) and quantifying the long-term performance (Gledhill et al., 1980). However, most of these research projects have been conducted within fields such as aerospace that have distinct differences from civil engineering applications. These differences cover a wide range of variables from material characteristics to in-service conditions. Loading, curing conditions, operating environment, material production, joint geometry and manufacturing conditions are some examples of the aforementioned dissimilarities (Karbhari et al., 2003). In addition, the useful service life of civil infrastructures is often more than 80 years, with minimum maintenance and inspection requirements, compared with the relatively short service life and highly controlled conditions implemented in aerospace structures (Liao et al., 1998). As a result, in durability assessments of adhesively bonded joints used in civil engineering applications, most of the available experimental data, testing methods and so on are not directly applicable. Furthermore, this limitation highlights the need for in-context assessments of the available literature based on their intended use. With the increased application of FRP composites in civil infrastructure in the early 2000s, Bakis et al. (Bakis et al., 2002) wrote a comprehensive state-of-the-art study targeting the construction sector, in which the authors concisely addressed the development and potential application of FRP composites, as well as the prevailing codes and standards. Concurrently, Hollaway and Cadei (Hollaway and Cadei, 2002) reported on progress in the upgrading and rehabilitation of metallic structures with advanced polymer composites. Although the advantages of the investigated rehabilitation method were confirmed, the adhesive material still remained the weakest link with respect to failure. Moreover, the authors emphasized the importance of determining in-service environmental issues associated with FRP bonding. To address the identified barrier of insufficient durability data for FRP composites used in civil infrastructure applications, Karbhari et al. (Karbhari et al., 2003) conducted a comprehensive durability gap analysis for various environmental conditions. They concluded their study with a list of common needs that are critical for the further implementation of FRP composites in civil infrastructure, irrespective of their intended operating conditions. Fawzia and Kabir (Fawzia and Kabir, 2012) reviewed the current research on the durability of CFRP-strengthened concrete and steel structures. The authors remarked that, in contrast to numerous durability studies of CFRP-strengthened concrete structures, the published data on CFRP-strengthened steel structures is minimal. To date, durability concerns remain an obstacle to the widespread application of FRPs in steel structures and they have been continuously accentuated by many other researchers (Shaat et al., 2004).

Recently, Heshmati et al. (Heshmati et al., 2015) reviewed the current research on the environmental durability of adhesively bonded steel/FRP joints to reflect on the durability gap and comment on the research needed in this field. It was concluded that the Hygrothermal ageing, the combined effect of moisture and temperature to be among the most severe exposure conditions. Exposure to constant humidity and temperature, wet/ dry cycles and hot/wet exposure in saline solutions are some examples of hygrothermal ageing. Adhesively bonded joints used in outdoor applications, such as bridges, are often exposed to aggressive environments and the combined effect of these service conditions may be more damaging than the adverse effect of each individual condition. The review of current studies at joint level is evidence of a lack of systematic ageing conditions aimed at clearly identifying the individual and combined effect of each environmental parameter. It is therefore a future research need to conduct durability tests at both material and joint level with minimum variants each time. In addition, long-term exposure to natural weathering scenarios is very rare at material level and is not available for joints. The results of these tests, as the most realistic representative conditions, are necessary for qualitative performance evaluations of CFRP-to-steel bonded joints and to validate accelerated testing procedures.

4 APPLICABILITY OF VACUUM RESIN INFUSION AND HEATING FOR STRENGTHENING OF STEEL MEMBERS

Two processing techniques commonly used in the repair of structures via bond of FRP onto the substrate due to their simplicity and lower capital cost are known as the pultruded plate and wet lay-up techniques. The pultruded FRP plate and wet lay-up systems both involve the curing of resins of up to several days under ambient conditions to achieve full load capacity. This can slow down the production rate and makes it hard to maintain composite uniformity (e.g. alignment of the fibres, proper resin impregnation, sufficient compaction of fibres) and the thickness steady (Hadigheh and Kashi, 2018). The quality of layups highly depend on the operator's skill and possibility of entrapped air voids inside the composite is high that can result in deterioration and reduction of durability (Hadigheh et al., 2015).

With the wide application of the composite materials in the strengthening of infrastructures, new processing techniques with higher quality are necessary to achieve the reliable FRP repairing systems (Hadigheh et al., 2015). Amongst automated techniques, the vacuum and resin infusion (V&RI) and the vacuum and heat (V&H) can be employed as alternatives for the contemporary fabrication methods due to their simplicity in moulding and cost effectiveness. These automated techniques have been used in aeronautics, marine, and automotive industries for production of high performance composites. Impregnation of the fibres in the V&RI is carried out by injection of the resin through a vacuum consolidated chamber (Figure 3a) while the V&H involves application of heat over pre-impregnated fibres in the presence of the vacuum (Figure 3b). Vacuum evacuates bonded surface from the air and provides a safe and reliable source of power for distribution of the resin over the fibre. These two mechanisms lower porosity level and subsequently improve mechanical properties of composite (Hadigheh et al., 2015). Curing takes place under vacuum condition for both methods, while in the V&H curing is also accompanied with an elevated temperature.



(a) (b)

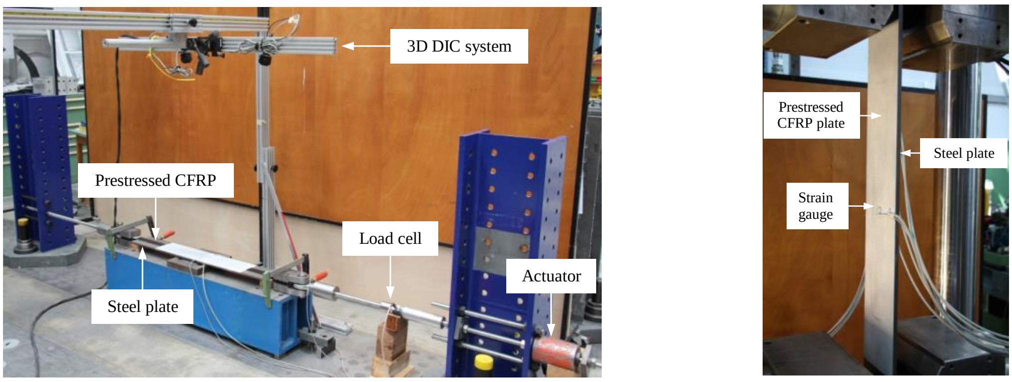
Figure 3. Schematic view of processing techniques for attachment of FRP on the substrate; (a) vacuum and resin injection (V&RI technique), (b) vacuum and heat (V&H technique).

In the V&RI and the V&H techniques, the cure of laminates is under control, and therefore, the desirable thickness of the composite based on design requirements is achievable. An added advantage of the V&H processing technique is the ability to achieve a higher glass transition temperature (T_g) for the resin. The mechanical properties of a bonded FRP reinforcement decrease when it experiences temperatures higher than T_g. Complex geometries can be efficiently constructed by the V&RI or the V&H. In addition, a composite with high quality, in terms of the mechanical and microstructural properties, is achievable. These techniques are repeatable and are able to achieve high fibre-to-resin ratio. Since in V&RI or V&H process the whole system is confined, the release of the volatile organic compounds or contact with composite is minimized.

The vacuum resin infusion is used in fabrication of FRP bridges for replacement of deteriorated structures, e.g. Bennett's Creek in US and West Mill Bridge in Oxfordshire, UK. Significant strength was achieved for the replaced bridge through prototype and field proof tests applying a full-scale load as well as less construction time and cost effectiveness (Alampalli et al., 2000). Vacuum and resin infusion/heat technique has recently been used to investigate the performance of steel-FRP shear walls made by pre-pregs (Petkune et al., 2016), and patch repair of steel I-beams with pre-pregs (Manalo et al., 2016). The application of vacuum and resin infusion/heat has not been fully investigated in structural strengthening. Hadigheh and Kashi (Hadigheh and Kashi, 2018) showed that wet lay-up and pultrusion methods were used in more than 50 per cent of the FRP applications, while just 3 per cent of research exercised the V&RI or the V&H. This figure indicates the lack of published data on the use of automated techniques in structural engineering.

5 DEVELOPMENT OF PRESTRESSED BONDED CFRP RETROFIT SYSTEMS

Prestressed CFRPs have been proven to be quite effective in enhancing the performance of steel beams (Hosseini et al., 2018b, Ghafoori and Motavalli, 2015a) and plates (Hosseini et al., 2019b, Hosseini et al., 2018a, Hosseini et al., 2017). It has been shown in previous studies that application of a compressive stresses to structural members (using prestressed FRPs) can enhance the flexural capacity (Ghafoori and Motavalli, 2013), buckling strength (Ghafoori and Motavalli, 2015b) and fatigue behaviour (Ghafoori et al., 2015c, Ghafoori et al., 2015b, Ghafoori et al., 2015a) of civil structures. Hence, it is evident that the use of prestressed CFRPs has several advantages over the nonprestressed reinforcements, owing to their ability to reduce the permanent tensile stresses in the strengthened member. Consequently, the application of prestressed CFRPs is of utmost interest for the fatigue strengthening of existing metallic structures, as it can reduce the mean stress levels, and consequently, enhance the fatigue life of the strengthened member. Despite this great advantage, fewer attempts have been made to use prestressed bonded reinforcement (PBR) systems for the strengthening of steel members in practical cases. This can be explained by the fact that high prestressing levels cannot be reached in PBRs, owing to the premature failure by debonding of the composite reinforcement from the steel substrate (Martinelli et al., 2019, Hosseini et al., 2019a, Hosseini et al., 2018c).

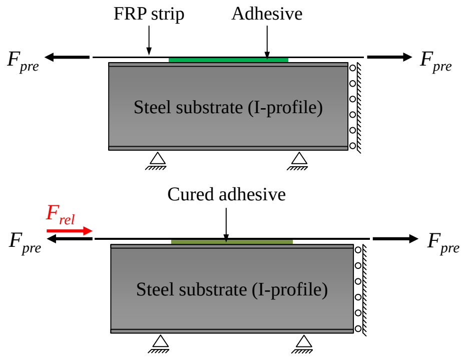


(a) (b)

Figure 4. (a) Prestressing setup; (b) uniaxial tensile test on prestressed CFRP-strengthened plate.

To further study the feasibility of using PBR solutions for the strengthening of existing metallic structures, systematic experimental, analytical and numerical studies have been conducted at the Structural Engineering Research Laboratory of Empa. The Experimental results of static tests, performed on prestressed bonded CFRP-strengthened steel plates (see Figure 4) revealed that even though adhesively bonded CFRPs can transfer certain levels of prestressing force to the steel substrate, the available bond capacity of the PBRs is relatively low for carrying the external service loads on the strengthened member (Hosseini et al., 2019b). Consequently, to better investigate the behavior and capacity of prestressed CFRP plates bonded to steel substrate, a special real-scale lap-shear setup was constructed at Empa (see Figure 5), and sets of lap-shear and prestress release tests were performed on CFRP-to-steel adhesively bonded joints cured at room temperature and at elevated temperature. Experimental results revealed that in the case of CFRP-to-steel bonded joints cured at room temperature, the debonding loads of prestress release tests were slightly lower than the corresponding loads in lap-shear tests. It was observed that in the prestress release tests, the slip and separation of the CFRP plate with respect to the steel substrate had the same order of magnitude. Consequently, the lower debonding load obtained in prestress release tests compared to the lap-shear tests, was attributed to the mixed mode I/II (tensile/shear) state of the fracture in the adhesive layer in the prestress release test (Martinelli et al., 2019).

It was also observed that the accelerated curing (AC) of the epoxy adhesive based on heating can be a promising alternative to the conventional room temperature curing for the strengthening of steel members with prestressed bonded CFRP plates. It is clear that the AC can be certainly advantageous in practical applications in reducing the overall strengthening time. Furthermore, the AC would essentially improve the installation progress in a practical strengthening project dealing with prestressed CFRP plates, where the prestressing system needs to stay in place to maintain the prestressing force constant during the curing period (Hosseini et al., 2018c). Considering the certain advantages of using prestressed reinforcements, as well as the aesthetic superiority of PBRs (compared to the mechanical anchorages), it is of great significance to further investigate the bond behavior and debonding capacity of PBR solutions, in particular to better realize the coupled effects of moderately high service temperatures, creep, and fatigue.



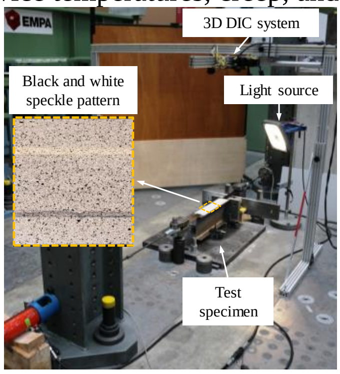


Figure 5. (a) principle of a prestress release test; (b) special setup for single lap-shear and prestress release tests to study the bond behavior and debonding capacity of CFRP-to-steel.

6 STRENGTHENING OF AN OLD HISTORIC AUSTRALIAN BRIDGE

The performance of nonprestressed CFRP plates for the strengthening of existing metallic bridges was demonstrated on a 19th–century roadway metallic bridge in Australia, i.e., the Diamond Creek Bridge that was built in 1896 (see Figure 6). Based on several laboratory experiments, a linear epoxy adhesive with a relatively high glass transition temperature (T_O = 46.6 °C) was selected for the on-site application of the CFRP plate (Hosseini et al., 2019a). Sets of truck loading tests were performed on the bridge before and after the strengthening to evaluate the performance and efficiency of the nonprestressed bonded CFRP reinforcements. Furthermore, a wireless sensor network (WSN) system was installed on the bridge for the long-term strain and temperature monitoring (see (Ghafoori et al., 2018) for further details).

The truck loading tests performed on the bridge demonstrated that the bending stresses generated in the top and bottom flange of the cross I-girder were reduced by approximately 15% after the girder was strengthened using the nonprestressed bonded CFRP plate. Furthermore, on-site strain measurements revealed that during the truck loading tests the peak interfacial shear stress at the CFRP plate extremities was approximately equal to 0.45 MPa, which is far less than the respective value tests that can be obtained in a short-term lap-shear (approximately 17.4 MPa). Therefore, it can be concluded that when fatigue strengthening of real-scale steel girders using nonprestressed bonded CFRP plates is of interest, the CFRP-to-steel bond capacity does not necessarily play the main role in the choice of the most appropriate epoxy adhesive. Long-term results obtained from the WSN system revealed that the maximum diurnal temperature change during the one-month period after the strengthening generated a stress range of 39.9 MPa in the mid-length of the bonded CFRP plate, which is almost equal to the maximum stress level generated in the CFRP reinforcement, due to truck loading.

Nonprestressed bonded CFRP reinforcements are relatively simple and easy to be used for the strengthening of existing metallic members; this aspect makes them quite attractive, despite their relatively lower efficiency compared to the prestressed unbonded retrofit systems (Ghafoori et al., 2018). The futures research studies might further concentrate on the performance and efficiency of such bonded systems for the strengthening of metallic details and connections.

(a) (b)

Figure 6. (a) 122-year-old Diamond Creek Bridge in Australia under daily traffic; (b) strengthening of a cross-girder using bonded CFRP plate.

7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORKS

This study has addressed various aspects of short- and long-term behavior of CFRP-to-steel bonded joints. The following conclusion points and recommendations for future works can be made:

- A critical evaluation of the model uncertainty of adhesively bonded CFRP-to-steel joints was performed. The model factor, which was highly dependent on input parameters, was decomposed into a systematic part and a residual random factor. The model prediction was significantly improved after modification.
- Moisture and temperature and their combined effect were identified as the most critical environmental factors. Future research is needed to be performed on naturally aged specimens to confirm the available results from accelerated tests in literature to establish a link between them.
- Vacuum and resin/heat infusion techniques provide asset owners with the opportunity to harness proven composite technology to upgrade and repair a wide range of structures.

However, still future research is required for adaptation of these methods in structural engineering applications, including using suitable vacuum pressure, selection of the resin with appropriate viscosity, improving permeability of distribution media, optimum positioning of vacuum and resin injection inlets, optimal temperature and curing time taking into account substrate condition, and improving vacuum bagging to optimize capital investment for large- or small-size operations.

- The results of an extensive experimental study performed at Empa revealed that the PBRs have potentials to be used for the strengthening of existing metallic members, especially owing to their aesthetic superiority compared to the mechanical anchorage alternatives. Therefore, future research studies in this domain can be dedicated to study the behavior and capacity of PBR systems under moderately high service temperatures, creep, and fatigue.
- On-site strain measurements revealed that the bending stresses generated in the top and bottom flange of the cross-girder in Diamond Creek Bridge were reduced by approximately 15% after the nonprestressed bonded CFRP strengthening. Considering the simplicity of such a strengthening system, it is believed that more field applications and long-term monitoring of this type of strengthening can further increase the overall trust on the bonded CFRPs, and eventually lead to their wide-spread application for the strengthening of existing metallic bridges.

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