Interface response of CFRP fabrics for concrete substrates enhanced with toughened epoxy adhesive layers.

Dimitra V Achillopoulou1,2*, Antonino Montalbano3, Fabien Choffat4

1Assistant Professor, Civil Engineering Department, Democritus University of Thrace, Xanthi, Greece
2Visiting Researcher, Civil and Environmental Engineering, University of Surrey, United Kingdom
3Sika Services AG, Zurich, Switzerland
4Sika Technology AG, Zurich, Switzerland
*Corresponding author, dimiachi@civil.duth.gr; d.achillopoulou@surrey.ac.uk

Abstract
Superstructures such as reinforced concrete bridges, often suffer from exposure to extreme corrosive environments. The corrosion of the reinforcement leads to a decrease of their capacity and their structural performance needs to be upgraded with strengthening measures. Lately, the use of Fiber Reinforced Polymers (FRP) in retrofitting schemes has attracted a lot of attention. In this paper the interface response of adhesively bonded Carbon FRP (CFRP) fabrics applied on concrete substrates is investigated. This paper deals with the study of the integration of CFRP fabrics using different adhesive layers as the composite’s matrix, first using a conventional adhesive and next using an enhanced toughened adhesive layer. Two different scenarios of substrate integrity were studied: a) healthy concrete and b) substrate with corrosion products. The bond-slip behavior of the interfaces between concrete and the laminated fabrics was investigated with a modified double shear test configuration. The use of the toughened matrix increases the shear stresses up to 61% in failure, nonetheless in significant lower ratio of strains. The corrosion reduces the maximum shear stresses of the interface up to 20% and the corresponding strains up to 23% in failure. For the scenario were the toughened matrix was used, there is a shift in the response from a pseudo-ductile to linear with a tendency to fully elastic. The crack propagation is depicted in distinct stages. The use of toughened adhesive layers with reduced stiffness shifts the mindset of creating high stiffness retrofitting solutions to achieve high mechanical performance and still ensures an efficient strengthening response.

Keywords: CFRPs, toughened adhesives, nanoparticles, interfaces, corrosion.

Introduction
Nowadays, the existing infrastructure stock of which the average bridge is 50-70 years old phases problems concerning maintenance. The bridge owners are dealing with a large number of structurally and functionally deficient bridges which are in need for upgrading (Sika 2021). Given the importance of those structures as well as the resources spent over the years, the repair and strengthening are inevitable. There is a special focus on criteria such as the safety, continuity of use, and above all, failure prevention the following factors are taken into consideration throughout the life-cycle of a bridge so the functionality and structural capacity is assessed:
1. Increase in the traffic load and intensity (overloading, extreme seismic events),
2. Concrete damages (cracks) and loss of steel cross section due to environmental attacks e.g. steel reinforcement corrosion, chloride ingress, freeze/thaw action, deicing salts carbonation, water ingress
3. Damage due to collision,
4. Damage (cracking) due to fatigue,
5. Changes in the design codes,
6. Inappropriate aggregate consistency e.g. Alkali Aggregate Reaction (AAR),
7. Deviations/errors in construction e.g. poor construction quality, stray electrical current, inadequate steel coatings,
8. Additional safety requirements,
9. Improving traffic conditions e.g. widening of the bridge deck,
10. Structural changes/displacements, extreme phenomena and events, climate change, e.g. creep and shrinkage, seismic events, scour, vibrations, increased thermal exposure, floods.

**FRP strengthening measures for RC bridges**

A strengthening strategy starts by assessing the existing condition of the asset and further by defining the objectives of strengthening and repair. For the case of a bridge, this is a function of the following parameters:
1. Bridge structural characteristics (type, span length etc.),
2. Superstructure material characteristics (strength, steel, other),
3. Age profile (assessment of the residual life of the asset),
4. Assessment of the structural and functionality condition of the asset,
5. Demands for the construction of new bridges in densely populated areas,
6. Existing/available strengthening activities,
7. Maintenance issues/activities,
8. Traffic/commute needs and priorities,
9. Life cycle issues and independencies with other urban projects,
10. Resources.

The decision of strengthening technique and strategy is strongly based on the technical feasibility of the bridge retrofitting scheme, as well as the existing condition of the asset. The design of the strengthening scheme must be suitable for the retrofitting target and satisfy the requirements of the asset. Hence, it should meet the functional and structural requirements of the bridge, including resistance (strength, flexural, shear, torsional), ductility, stiffness, stability, dynamic response, durability (exposure conditions), compatibility with substrate (bonding of old and new material) and disturbance of the existing response/geometry/function.

A lot of attention has been given to the strengthening schemes using Fiber Reinforced Polymers (FRPs). FRPs, except for the high performance and resistance, are also cost-effective materials compared to conventional construction materials such as steel and concrete, especially considering maintenance costs. Durability matters, in some cases, provide enough benefit to make composites a better choice compared to steel and concrete. Table 1 summarizes strengthening techniques with FRPs available for retrofitting of the structural members (e.g. beams, piers, decks) for different reasons (e.g. shear, flexural, torsional strengthening), listing their advantages and disadvantages. They are designed and manufactured to resist chemical corrosion and high temperatures. It is also worth noticing the environmental impact of the FRPs material. The green aspect/dimension lies on the energy consumption to produce FRP composites is lower than that for traditional construction materials (Sunter et al. 2015) such as steel and concrete. Also, it is possible to recycle the FRP materials. FRPs can be crushed and granulated and reused. The response of the strengthening measure and each FRP system is a matter of question. Each strengthening system exhibits different kind of premature/dominant failure (Table 1) meaning that the response of the interface of the FRP system is of crucial importance for the overall efficiency of the intervention.

| Strengthening Scheme | Type | Advantages | Disadvantages | Strengthening/control | Dominant failure |
|----------------------|------|------------|---------------|------------------------|-----------------|
| Externally Bonded FRP (EB FRP) | | | | | |
| plates | high strength to weight ratio | low temperature resistance | flexural (Rollins 2015) | concrete cover separation/peeling |
| sheets | ease and speed of application (Wang et al. 2013) | high cost of epoxy resins | shear (Heiza et al. 2014) | interfacial debonding |
| strips | high corrosion resistance (Rollins 2015) | impractical wet application | compression-confine | |
| wraps | good bonding with epoxy-based adhesives | impractical application during low temperatures | torsional | |
| | undistrupted asset’s operation (Wang et al. 2013) | poor vapor permeability | crack (Rollins 2015) | |
| | enhancement of ductility in confinement solutions | incompatibility of epoxy resin and concrete | | |
| | | difficult damage detection and assessment on concrete substrate | | |
| Mechanically Fastened FRP (MF FRP) | Near Surface Mounted FRP (NSM FRP) | Sprayed FRP |
|-----------------------------------|-----------------------------------|-------------|
| bars, strips, fasteners, threaded bolts, expansion anchor bolts, power-actuated fasteners | bars, strips, rods | short randomly oriented chopped fibres, polymer matrix |
| - high strength to weight ratio (Wang et al. 2013) | - high strength to weight ratio (Wang et al. 2013) | - avoids unidirectional composite material |
| - prevents from premature peeling/delamination (Rollins 2015) | - little repair material required | - suitable for complex surfaces, geometries & joints |
| - allows easier FRP post-tensioning (Rollins 2015) | - cost effective | - forms a continuous strengthening layer |
| - surface preparation not required | - less prone to premature failure | - enhanced bonding vs EBFRP (Yang and Li 2019) |
| - ease and speed of application (Bank 2004) | - better protection of FRP material against wear, fire and impact loads | - quality control issues of mixing the fibres and resins (Lee and Hausmann 2004) |
| - good temporary measure due to reversibility (Napoli et al. 2013) | - good durability | - requires surface preparation (Yang and Li 2019) |
| - installation requires common hand tools | - good fatigue performance (Abdallah et al. 2020) | - practical limitations in fibre placement around sharp corners |
| - can be performed by unskilled labour (Lopez et al. 2005) | - high bond efficiency vs EBFRP (Al-Obaidi et al. 2020) | - premature debonding at interface (Heiza et al. 2014) |
| (Heiza et al. 2014) | (Triantafillou et al. 2006) | (Triantafillou et al. 2006) |
| - premature peeling/delamination (Rollins 2015) | - requires surface preparation | - premature peeling/delamination (Rollins 2015) |
| - unprotected FRP Material against wear, fire and impact loads | - unidirectional FRP debonding failure (Sharaky, I. A. et al. 2015) | - unidirectional FRP cracking (Sharaky, I. A. et al. 2015) |
| - bond affected by aggressive environmental conditions (Heiza et al. 2014) | - anchors susceptible to corrosion | - anchors susceptible to corrosion |
| (Heiza et al. 2014) | - less economical vs steel PT anchors | - less economical vs steel PT anchors |
| | - complicated installation (Mohee et al. 2016) | - complicated installation (Mohee et al. 2016) |
| | - fastened joints exhibit stress concentrations (Abdallah et al. 2020) | - fastened joints exhibit stress concentrations (Abdallah et al. 2020) |
| | - significant slip at concrete-FRP interface (Napoli et al. 2013) | - significant slip at concrete-FRP interface (Napoli et al. 2013) |
| | - fasteners may damage concrete substrate (Lopez et al. 2005) | - fasteners may damage concrete substrate (Lopez et al. 2005) |
| | - requires significant drilling | - requires significant drilling |
| | - danger of galvanic corrosion of internal reinforcement if fasteners are in contact with steel (El-Maaddawy 2014) | - danger of galvanic corrosion of internal reinforcement if fasteners are in contact with steel (El-Maaddawy 2014) |
| | - decreases ductility | - decreases ductility |
| | - debonding failure | - debonding failure |
| | - requires groove preparation | - requires groove preparation |
| | - decreases moment redistribution behaviour (Abdallah et al. 2020) | - decreases moment redistribution behaviour (Abdallah et al. 2020) |
| | - flexural (Al-Obaidi 2020) | - flexural (Al-Obaidi 2020) |
| | - shear | - shear |
| | - compression (Heiza et al. 2014) | - compression (Heiza et al. 2014) |
| | - crack (Abdallah et al. 2020) | - crack (Abdallah et al. 2020) |
| | - debonding/pull-out of rods (Sharaky, I. A. et al. 2014) | - debonding/pull-out of rods (Sharaky, I. A. et al. 2014) |
| | - concrete cover separation/peeling (Peng et al. 2017) | - concrete cover separation/peeling (Peng et al. 2017) |
| | - tensile yielding & concrete crushing | - tensile yielding & concrete crushing |
| | - concrete cover crushing and yielding of steel (Lee and Hausmann 2004) | - concrete cover crushing and yielding of steel (Lee and Hausmann 2004) |

**Epoxy matrix**

Epoxy matrices have several properties that make them the best option among thermosetting resins for most engineering applications, among which flexibility, no volume contraction and high adhesion. Two-component (2C) epoxy adhesives allow high-strength bonding of lightweight structures by chemical curing at both low (room temperature) and high (> 80 °C) temperatures. These adhesives
normally show a relatively high tensile modulus and withstand high static loads. Due to the brittle fracture behaviour of their matrix, however, standard epoxy adhesives are characterized by a limited resistance to dynamic loads, such as impact and cyclic loads. For this reason, industrial research has investigated toughening methods for epoxy matrices during the past years, introducing a number of 1C and 2C epoxy adhesives with an improved impact resistance (Meier et al. 2020).

**Toughened adhesives**

Toughening normally results in a matrix with lower stiffness, as the content of dissolved toughener in the matrix increases. Partially, this is intended because material with lower stiffness usually has a higher toughness. The smaller and the better dispersed the toughener particles are, the higher the toughness is. One chemical approach to form well distributed small particles into a cured epoxy matrix is using reactive toughening polymers. The toughened adhesives are expected to absorb more energy before debonding, especially under dynamic load. The toughening for those products is done by incorporation of Polyurethane (PU) rubber like particles into the two component (2C) epoxies. The curing aims at high amounts of elastic domains respecting particles, as small as possible in size and well connected as well as well distributed in the primarily stiff epoxy matrix. However, this process gives the matrix high flexibility, as the content of dissolved toughener in the mix increases. Most of the structural car body repair adhesives in the market are highly stiff and as expected show a low impact peel resistance (toughness) which may also result in lower fatigue performance. -On the other hand, structural performance requires a certain stiffness, thus a significant decrease of strength is not desired. As such, an optimal combination of high mechanical performance and increased toughness is the strengthening concept introduced to retrofitting schemes, as shown in Figure 1 (SmartCore-Sika).

![Figure 1](image1.png)

**Figure 1. REM images of fracture surfaces of:** a) an untoughened epoxy matrix and b) a toughened epoxy matrix with well-distributed approximately 1 µm rubber-like particles formed upon curing.

**Experimental campaign**

**Materials**

Twelve concrete blocks are presented in this study with dimensions 150x150x250mm and were prepared according to EN 206-1, EN 197-1-2011; ACI 2011. The concrete mix had a 28-day compressive strength of 37.5 MPa corresponding to a tensile strength of 3MPa. All blocks contained a steel rebar (500MPa) of 18mm diameter in the middle of the cross section placed longitudinally to the concrete block. The CFRP fabrics (SikaWrap 301-C) were bonded symmetrically on opposite sides of the concrete prisms at a bond length of 200mm with dry lay-up process, using different 2C epoxies curing at ambient environment. First a standard epoxy was applied (Sikadur®-330) and next the application was repeated using the newly developed toughened epoxy adhesive (Sikadur®-370) designed for fatigue resistance long lasting reinforcement of steel bridges (Sika Group 2021). Table 2 resumes the mechanical properties of the materials.
Table 2: Mechanical properties of CFRPs [ref. Sika product data sheet].

| material          | density ρ [kg/L] | tensile strength σu [MPa] | E-modulus (0.05-0.25%) [GPa] | tensile strain ε (EAB) [%] |
|-------------------|------------------|---------------------------|-----------------------------|---------------------------|
| SikaWrap 301-C    | 1.8              | 4900                      | 230                         | 1.7                       |
| Sikadur®-330      | 1.4              | 29                        | 4000                        | 1                         |
| Sikadur®-370      | 1.7              | 30                        | 5000                        | 2.5                       |

Accelerated corrosion
The corrosion conditions were simulated in the lab using NaCl solution and a current flow in a tank. Six concrete prisms were exposed to wet conditions in a special tank. They were bathed in a 3.5-5% weight NaCl-water solution (Figure 2a), which covered one third of the cross-section size of the concrete blocks (van Zijl and Paul 2018, Dodds et al. 2017, Otieno et al. 2016). A low ratio of corrosion of the steel rebar cross-section is created almost equal to 6% with a continuous power supply (≈1mA) (Batuwitage et al. 2017) wired in the steel rebars for about three weeks. The crack opening of the concrete blocks (w=0.1-0.35mm) and the loss of rebar cross section (loss of diameter equal to 0.4mm) simulates exceeding service limit states conditions but not severe deterioration in ultimate limit states (Figure 3). The samples were also exposed, except for the wet conditions, in dry conditions on-site, before the application of the FRPs (Otieno et al. 2017). After this period, the tensile strength of concrete was assessed with other experiments from the international literature to avoid patch repair in the case of experimental measurement with pull-off tests (EN1542 1999).

FRPs application
The composite strengthening systems were bonded symmetrically on opposite sides of the blocks with a bonding length of 200mm on each side. The fibre orientation of the fabrics was 0° along the longitudinal direction of concrete blocks. The systems were applied with a dry lay-up process and according to the technical specification of Sika. The interfaces were treated properly to have a laitance contaminant free, open textured surface and were cleaned with air pressure to remove loose material, dust and rust (Figure 2b/i-iii). The two components’ epoxy adhesives were mixed according to the manufacturer’s recommended weight ratio and time (4:1 for Sikadur®-330 and 100:74 for Sikadur®-370). Special attention was given to the rolling direction of the application which was parallel to the fibers towards the same direction (Figure 2b/iv). The composites are left to cure at ambient conditions (20°C, 50% relative humidity-RH) for at least a week before testing (Figure 2b/v).

![Figure 2. Experimental campaign, a) accelerated corrosion, b) FRP application, c) double-lap configuration.](image-url)

Testing
This study adopts a modified double lap shear test (Figure 2c). This involves instead of the classic two concrete blocks, only one concrete block where the FRPs are applied and are gripped to the protruding end. The concrete block lays on a hollow support which permits slip and is hanged from the gripped
ends of the FRPs that are fixed to a rigid steel frame. This alteration of the setup limits the relative slips of the interfaces of the two different blocks, eliminates slips at the gripped ends of the FRP and at the same time permits direct shear stress measurement. The tests were performed on a compression machine at a speed of 1mm/min at a room temperature (20°C). The measurements of the deformation of the central part of the CFRP at the central path were recorded using a high accuracy laser sensor. Also, two Linear Displacement Transducers (LDVT) with a maximum capacity of 100mm, were used to measure the displacement of the upper level of the concrete block and the grips.

**Results**

**Shear stress vs strain**

On the described specimens where fabrics are applied are referred to as concrete blocks with laminated sheets/fabrics (sh330x3Hl, sh330x3Cr) bonded with the two epoxies. The experimental results are presented in shear stress vs shear strain diagrams. The curves represent the average curve of the three specimens of each group. The results are also listed in Table 3.

Concrete blocks with the laminated fabrics bonded with the epoxy adhesive layer Sikadur®-330, present a response in three distinct stages, shown in Figure 3a. The low elasticity of the matrix (epoxy layer) in combination with the increased strain range, permit the epoxy to absorb more energy before failure. In the first stage the fabric is under tension (Stage I: linear elastic) in a linear rate. The direction of the laminated sheets’ fibers that are in parallel to the loading direction prevents bridging the crack propagation. In the second stage, there is a progressive crack initiation of the epoxy layer leading to crack opening, followed by a non-linear elastic yielding branch up to the transition point (Stage II: non-linear elastic yielding). The transition point (τ\text{trans}, γ\text{trans}) practically corresponds to the further propagation of the crack pattern at the resin and the substrate and the overall connection of the two materials. The third stage is characterized by major cracking both at the adhesive layer and the substrate. Plastic regions are created at the concrete, and especially at the initial debonding area at a distance approximately equal to 5 cm from the loading end. At the ultimate point of this stage (Stage III: major cracking), the specimens exhibit debonding of the FRP (τ\text{frp}, γ\text{frp}). The failure mode is mainly caused due to adhesion loss at the delamination area and no FRP rupture is met (Figure 4b).

The effect of the corroded steel rebars on the interface response of this group is also shown in the same Figure. The green dashed line represents the average curve of specimens with corroded steel rebar with laminated sheets applied on the concrete substrate with epoxy adhesive layer Sikadur®-330, whereas the red solid line represents the average curve of the healthy specimens containing the same epoxy. There is a clear difference in the response in both cases. The interface of the substrate with corrosion products (330_corroded_ave) presents a 20% decrease in shear strength (τ\text{frp}) and 24% lower shear deformation (γ\text{frp}) at the ultimate point (Table 3). Also, the transition point is shifted to lower values of deformations (52%) and strength (18%). The leached corrosion products laying on the sides of the concrete prisms and the minor strains due to the initiation of corrosion are considered practically as mass disturbance and create regions of altered consistency and resistance. Also, even in such early stages of corrosion, which corresponds to corrosion initiation and to allowable bond values of the substrate for immediate interventions, the cracks in the concrete mass in combination with the rust laying on the interface, makes the connection with the FRP strengthening scheme weaker.

Sikadur® 370 is a new developed toughened epoxy adhesive combining high toughness with higher stiffness and strength, also showing a high fatigue strength. Its good adhesion and good anti-corrosion performance make it an optimal solution to be applied in extreme corroded environments even onto concrete substrates (Achillopoulou 2021). A matrix having 25% higher stiffness presents a different response (sh370x3HL, Table 3). This group of specimens having laminated sheets bonded with epoxy adhesive layer 370 (Sikadur®-370) presented a rather brittle behavior. This is illustrated in Figure 3b, where it is noted that the tougher the matrix is, the stages II and III coincide. Its intrinsic toughness is proven to enhance the capacity of the substrate to bear the shear stresses, though it presents a rather elastic response. The transition point in this case is remarkably clear and decreased per 80% in respect to the corresponding case of Sikadur®-330 layer. This means that the failure propagation of the substrate starts at different stress rates. Even though there is a distinct transition point in almost the
same levels of shear deformations yet in higher values of shear stresses (70% higher at transition point and 2.5 times higher at ultimate), the crack pattern both in the substrate and in the adhesive layer propagates simultaneously up to the debonding point of the strengthening system. This intrinsic toughened adhesive layer Sikadur®-370 is designed for steel substrates and especially suitable for fatigue cracking applications. The crack width in the cases of concrete substrates is larger than fatigue cracking in steel substrates. In combination with the stiffness of the matrix, the response alters from pseudo-plastic (case of Sikadur®-330) to brittle and the failure mode from adhesive-cohesive to FRP rupture (Figure 4d).

For this strengthening scenario using the toughened matrix the effect of corrosion and rust is also examined illustrated also in Figure 3b with the blue dashed line. In that case the response is similar to the healthy substrate case, however a decrease in the values of shear stress and strains is noted. The difference of the corresponding healthy case is almost 43% in ultimate shear stress and 62% in shear strains at the ultimate point. Also, the stages are compressed and the transition point is presented earlier in almost half the strains and stresses of the healthy substrate.

In terms of the absorbed energy, specimens with toughened epoxies exhibit on average 15% higher energy, when the substrate is healthy. In the case that rust has leached on the surfaces and corrosion process has initiated, then the response differs significantly. For the case of the standard epoxy, the absorption of energy decreases on average 40%, whereas, the toughened epoxies on corroded substrates the energy absorbed in almost one third of the corresponding standard epoxy.

In terms of the absorbed energy, specimens with toughened epoxies exhibit on average 15% higher energy, when the substrate is healthy. In the case that rust has leached on the surfaces and corrosion process has initiated, then the response differs significantly. For the case of the standard epoxy, the absorption of energy decreases on average 40%, whereas, the toughened epoxies on corroded substrates the energy absorbed in almost one third of the corresponding standard epoxy.

Figure 3. Shear stress vs shear strain diagrams a) compatible epoxy, b) toughened epoxy matrix.

Figure 4. Failure modes of CFRP adhesively bonded in healthy or corroded substrate with compatible a), b) or toughened matrix c) & d).
Table 3. Experimental results of double lap shear tests.

|                | healthy substrate | with corroded products |
|----------------|-------------------|-----------------------|
|                | τ\text{trans} (MPa) | τ\text{u} (MPa) | γ\text{trans} (%) | γ\text{u} (%) | E (MJ/m³) | τ\text{trans} (MPa) | τ\text{u} (MPa) | γ\text{trans} (%) | γ\text{u} (%) | E (MJ/m³) |
| Hl330_1        | 1.25              | 1.48                 | 0.72              | 1.33          | 1.56      | Cr330_1            | 0.94              | 1.11              | 0.47              | 1.73       | 1.59      |
| Hl330_2        | 1.28              | 1.38                 | 0.57              | 1.46          | 1.76      | Cr330_2            | 0.99              | 1.20              | 0.32              | 0.60       | 0.51      |
| Hl330_3        | 0.82              | 1.37                 | 0.6               | 0.91          | 0.84      | Cr330_3            | 0.83              | 1.09              | 0.12              | 0.47       | 0.39      |
| average 330    | 1.12              | 1.41                 | 0.63              | 1.23          | 1.39      | average 330        | 0.92              | 1.13              | 0.30              | 0.93       | 0.83      |
| Hl370_1        | 1.97              | 3.58                 | 0.2               | 0.67          | 1.70      | Cr370_1            | 0.95              | 1.80              | 0.09              | 0.22       | 0.26      |
| Hl370_2        | 1.80              | 3.57                 | 0.12              | 0.63          | 1.59      | Cr370_2            | 1.30              | 2.20              | 0.14              | 0.25       | 0.37      |
| Hl370_3        | 1.94              | 3.56                 | 0.07              | 0.65          | 1.73      | Cr370_3            | 1.20              | 2.10              | 0.18              | 0.28       | 0.38      |
| average 370    | 1.90              | 3.57                 | 0.17              | 0.65          | 1.63      | average 370        | 1.15              | 2.03              | 0.14              | 0.25       | 0.34      |
| abs error 370-330 | 41%            | 61%                 | 263%              | 90%           | 15%       | abs error 370-330  | 20%              | 44%               | 122%             | 273%       | 147%      |

Conclusions

- The adhesive layer limits the substrate’s failure propagation, allow the fracture to happen in stages and absorbs satisfactory energy before debonding.
- Toughened epoxies exhibit a satisfactory response and can be a strengthening scheme that has a combination of low level of stiffness and high strain capacity. In this way, the absorbed by the epoxy energy is higher, and permits the failure to be dislocated at the FRP system and not at the substrate.
- Toughened epoxy adhesive layers have a rather brittle behavior. The tougher the adhesive is the more brittle the behavior becomes.
- The corrosion of the steel rebars embedded at the concrete substrate has a strong impact on the response of the FRP system. It results in lower levels of stresses and strains, ranging up to 20% for shear stresses and 23% for shear strains at the ultimate point for the standard epoxy and at around 43% and 62% respectively, for the toughened one. Also, the crack propagation is faster.

Acknowledgements

This study has received funding by the European Commission H2020-Marie Skłodowska-Curie Research Grants Scheme MSCA-IF-2018 (grant agreement no 845549: BRIFACE- Novel assessment of bridge retrofitting measures through Interface Efficiency Indices (InterFeis) using a Guided Wave-based monitoring method) in which Sika AG was industrial partner. The authors warmly thank the Reinforced Concrete and Seismic Design Laboratory of Democritus University of Thrace for collaborating on the experimental campaign.

References

Achillopoulou DV (2021) ‘‘Investigation of the bond behaviour of interfaces of CFRP sheet strengthening schemes enhanced with toughened epoxy adhesive layers in corroded concrete substrates’’ 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering COMPDYN 2021, 27-30 June, Streamed from Athens, Greece.’
ACI 318-1.(2011). Building Code Requirements for Reinforced Concrete, ACI, August.

Al-Obaidi, S., Saeed, Y. M. and Rad, F. N. (2020)“Flexural strengthening of reinforced concrete beams with NSM-CFRP bars using mechanical interlocking,” *Journal of Building Engineering*. Elsevier Ltd, 31. doi: 10.1016/j.jobe.2020.101422.

Abdallah, M., Al Mahmoud, F., Boissiere, R., Khelil, A., & Mercier, J. (2020). Experimental study on strengthening of RC beams with Side Near Surface Mounted technique-CFRP bars. *Composite Structures*, 234, 111716.

Bank, L. (2004) “Mechanically-fastened FRP (MF-FRP) – a viable alternative for strengthening RC members,” *FRP Composites in Civil Engineering - CICE 2004*, pp. 3–15. doi: 10.1201/9780203970850.ch1

Batuwitage, C., Fawzia, S., Thambiratnam, D., & Al-Mahaidi, R. (2017). Durability of CFRP strengthened steel plate double-strap joints in accelerated corrosion environments. Composite Structures, 160, 1287-1298.

Dodds, W., Christodoulou, C., Goodier, C., Austin, S., & Dunne, D. (2017). Durability performance of sustainable structural concrete: Effect of coarse crushed concrete aggregate on rapid chloride migration and accelerated corrosion. Construction and Building Materials, 155, 511-521.

El-Maaddawy, T. A. (2014) “Mechanically fastened composites for retrofitting corrosion-damaged reinforced-concrete beams: experimental investigation,” *Journal of Composites for Construction*. American Society of Civil Engineers, 18(2), p. 4013041

EN 197-1-2011 (2000). Cement-Part 1: Composition, specifications and conformity criteria for common cements, CEN.

EN 206-1, Concrete — Part 1: Specification, performance, production and conformity, CEN.

EN, B. (1999). 1542. Products and systems for the protection and repair of concrete structures-Test methods—Measurement of bond strength by pull-off. British Standard Institution, London.

Heiza, K. *et al.* (2014) State-of-the Art Review: Strengthening of Reinforced Concrete Structures—Different Strengthening Techniques, International Conference on Nano-Technology In Construction.

Lee, H. K. and Hausmann, L. R. (2004) “Structural repair and strengthening of damaged RC beams with sprayed FRP,” *Composite Structures*. Elsevier BV, 63(2), pp. 201–209. doi: 10.1016/S0263-8223(03)00156-9.

Lopez, A. *et al.* (2005) “Bonded and mechanically fastened FRP strengthening systems: A case study,” *Special Publication*, 230, pp. 1217–1234.

Meier T, Choffat F and Montalbano A., ‘Toughened 2k-Epoxy Adhesives: Structural Strengthening Of Steel Structures’, IABSE Congress – Resilient technologies for sustainable infrastructure September 2-4, 2020, Christchurch, New Zealand.

Mohee, F. M., Al-Mayah, A. and Plumtree, A. (2016) “ Anchors for CFRP plates: State-of-the-art review and future potential,” *Composites Part B: Engineering*. Elsevier Ltd, 90, pp. 432–442. doi: 10.1016/j.compositesb.2016.01.011.
Napoli, A., Bank, L. C., Brown, V. L., Martinelli, E., Matta, F., & Realfonzo, R. (2013). Analysis and design of RC structures strengthened with mechanically fastened FRP laminates: A review. *Composites Part B: Engineering*, 55, 386-399.

Peng, J., Tang, H. and Zhang, J. (2017) “Structural Behavior of Corroded Reinforced Concrete Beams Strengthened with Steel Plate,” *Journal of Performance of Constructed Facilities*. American Society of Civil Engineers (ASCE), 31(4). doi: 10.1061/(ASCE)CF.1943-5509.0001004.

Rollins, T. (2015) New and emerging methods of bridge strengthening and repair and development of a bridge rehabilitation website framework.

Sharaky, I. A. et al. (2014) “Flexural response of reinforced concrete (RC) beams strengthened with near surface mounted (NSM) fibre reinforced polymer (FRP) bars,” *Composite Structures*. Elsevier, 109, pp. 8–22.

Sika (2021) ‘Causes of Bridge deterioration’ https://gbr.sika.com/en/construction/concrete-repair/bridges/causes-of-bridge-deterioration.html (last access 07/2021).

Soleimani, S. M., & Banthia, N. (2012). Shear strengthening of RC beams using sprayed glass fiber reinforced polymer. *Advances in Civil Engineering, 2012*

Sunter D., Morrow W.R. III, Cresko J.and Liddel H. P. H., (2015) The manufacturing energy intensity of carbon fiber reinforced polymer composites and its effect on life cycle energy use for vehicle door lightweighting, 20th International Conference on Composite Materials At: Copenhagen, Denmark

Triantafillou, T. C. et al. (2006) “Concrete confinement with textile-reinforced mortar jackets,” *ACI Materials Journal*. American Concrete Institute, 103(1), p. 28.

van Zijl, G. P., & Paul, S. C. (2018). A novel link of the time scale in accelerated chloride-induced corrosion test in reinforced SHCC. *Construction and Building Materials*, 167, 15-19.

Otieno, M., Beushausen, H., & Alexander, M. (2016). Chloride-induced corrosion of steel in cracked concrete–Part I: Experimental studies under accelerated and natural marine environments. *Cement and Concrete Research*, 79, 373-385.

Wang, W. W., Dai, J. G. and Harries, K. A. (2013) “Performance evaluation of RC beams strengthened with an externally bonded FRP system under simulated vehicle loads,” *Journal of Bridge Engineering*, 18(1), pp. 76–82. doi: 10.1061/(ASCE)BE.1943-5592.0000324.

Yang, Z. and Li, J. (2019) “Double shear test on bonding mechanical properties of sprayed FRP and concrete substrate,” *Composites Part B: Engineering*. Elsevier Ltd, 162, pp. 388–396. doi: 10.1016/j.compositesb.2018.12.080.