Construction and Building Materials 363 (2023) 129818

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

A review on the advances of the study on FRP-Concrete bond under hygrothermal exposure

Rayhan Md Faysal [a,b], Md Mehedi Hassan Bhuiyan [a], Khondhaker Al Momin [a], T. Tafsirojjaman [c], Yue Liu [d,*]

[a] Department of Civil Engineering, Daffodil International University, Dhaka 1341, Bangladesh
[b] Department of Civil and Environmental Engineering, King Fahd University of Petroleum & Minerals, 31261 Dhahran, Saudi Arabia
[c] School of Civil, Environmental and Mining Engineering, The University of Adelaide, Adelaide 5005, Australia
[d] Research Institute of Urbanization and Urban Safety, School of Civil and Resource Engineering, University of Science and Technology Beijing, 30 Xueyuan Road, Beijing 100083, China

ARTICLE INFO

Keywords:
FRP-Concrete Bond
Hygrothermal
Bond Degradation
FRP sheets
FRP laminate
FRP-Concrete bond strength model

ABSTRACT

The environmental exposure dramatically influences the performance of externally applied Fiber Reinforced Polymer (FRP) in the long run. Temperature and humidity are two common environmental factors that alter the bond behavior of the FRP application. This paper summarizes the observations of different researchers regarding the effect of temperature and humidity together (also known as the hygrothermal effect) and separately on the durability performance of the FRP-Concrete bond itself and its elements individually. Furthermore, a comparison of performance between FRP Laminate and sheet has been presented for hygrothermal environments. Moreover, different approaches by researchers to model the FRP-Concrete bond, followed by the efforts to incorporate hygrothermal effects in it, are discussed. Finally, some of the authors' observations and directions for potential future work have been stated.

1. Introduction

Structures lose their original load-carrying capacity due to the degrading effect of continuous environmental exposures [1]. Therefore, those structures require rehabilitation to keep them functional. Several materials, including steel plate, ultra-high-performance concrete (UHPC), textile reinforced mortar (TRM), and fiber reinforced polymer (FRP), are available for rehabilitation of the existing structure. The application of UHPC in rehabilitation impedes due to a limited understanding of UPHC materials and the availability of accepted design codes [2]. Again, the corrosion tendency and heavy weight of steel plates cause inconvenience in strengthening existing structures [3]. The TRM performance as a strengthening material is also reported inferior compared to FRP [4]. On the other hand, FRP is widely used for strengthening because of its inherent properties such as non-corrosive [5,6], high tensile strength [7,8], stiffness, lightweight [9,10], ability to undergo large deformation without failure [11–13] and better flexibility [14,15]. The bond characteristics in-between FRP and concrete surface is proved crucial to the effectiveness of FRP strengthening [16–19]. This characteristic itself depends on many factors, which include the type and strength of FRP [20], surface preparation, strength and thickness of the adhesive [21], the strength of the substrate [22–24], environmental exposures [25–30], etc. The various environmental exposures include temperature, humidity, pollution, frosting, carbonation, chemical corrosion, seawater tidal action, etc. [31,32].

Several studies on FRP-Concrete bonds under various environmental exposures found detrimental effects on bond performance [33–39]. For example, Silva et al. [40] found that the bond strength was reduced by 31% after going through Freeze-thaw cycles. Similarly, Mikami et al. [41] found the bond strength decreased by 92% under specific environmental exposure. However, among all environmental exposures, the hygrothermal (combination of temperature and humidity) environment is reported to have the most crucial effect on the performance of the FRP-Concrete bond in the long run [42,43]. A comprehensive literature review on the hygrothermal effect on FRP-Concrete is needed to uncover the overall detrimental effect of this exposure. In this paper, different aspects of hygrothermal effects on the FRP-Concrete bond are presented to address the need.

* Corresponding author.
E-mail addresses: rayhanfaysal24@gmail.com (R.M. Faysal), mehedihassanbhuiyan.ce@diu.edu.bd (M.M.H. Bhuiyan), momin.ce@diu.edu.bd (K.A. Momin), tafsirojjaman@adelaide.edu.au (T. Tafsirojjaman), yueliu@ustb.edu.cn (Y. Liu).

https://doi.org/10.1016/j.conbuildmat.2022.129818
Received 6 April 2022; Received in revised form 9 October 2022; Accepted 17 November 2022
Available online 1 December 2022

2. Hygrothermal effect on the individual FRP-Concrete elements

Among the components of the FRP-Concrete bond, the FRP itself is reported to have good enduring against the hygrothermal effect [44]. However, the other two elements, adhesive and concrete substrate, have well-known effects due to hygrothermal exposure. The following subsections will discuss some of the effects revealed by different researchers.

2.1. Adhesive

Epoxy, a common adhesive in FRP-Concrete bond, is susceptible to Humidity/or water and temperature. Absorption of water into the epoxy, known as plasticization [45], is reported have responsible for the stiffness reduction of epoxy [46,47]. Water increases the free volume of epoxy [48,49], which increases the mobility of the polymer chain. As a result glass transition temperature (Tg) of epoxy reduces, resulting in a reduction of epoxy stiffness [50,51]. A similar decrease is observed due to the heat of increased temperature, especially when the temperature is more than Tg of epoxy [52]. Beyond Tg, epoxy turned into a rubbery state from a glassy state, hence losing its stiffness significantly. This physical change and corresponding stiffness reduction can also be explained by free volume theory [53]. The combining effect of the abovementioned two parameters, known as the hygrothermal effect in the literature, can cause severe alternation of the property of epoxy [54,55]. Chakraverty et al. [56] reported an 8% reduction in the Tg value of a typical glass fiber reinforced epoxy (GRE) under a specific hygrothermal environment. Equilibrium moisture absorption and diffusion coefficient are also greatly influenced by Hygrothermal conditions [57–59]. There is another hygrothermal effect known as the post curing process, which causes an increase in the density of cross-linking of epoxy polymer and hence reduces the internal stress [60]. The term “post-curing” here is used to refer to the secondary process of condensation of the cross-linking between polymer (epoxy) chains [60]. The “curing” also plays a vital role in forming the stiffness of epoxy resign at the early stage of epoxy application. Two weeks at room temperature is reported to have enough to complete 80–100% of curing [61]. Al-Lami et al. [62] investigated the epoxy performance in warm water (40°C) for up to 1500 h. The tensile strength and ultimate strain of the investigated epoxy had shown an increasing trend followed by decreasing trend in the abovementioned exposure. The rising trend can be credited to the beneficial effect of the post-curing process of epoxy, and the decreasing trend can be attributed to the negative effect of hygrothermal exposure as it eventually overturns the positive effect of the post-curing process [62]. Kumar et al. [63] studied various factors, including relative humidity and temperature of the environment, to study structural adhesive behavior. Their review suggests that the curing temperature and humidity predominantly affect the adhesive behavior in the long run. The existing practice is to keep the adhesives in the accelerated environment that it is supposed to experience in its service life for a period specified by standard code (i.e., AASHTO, ICC) to assess its performance. The one that satisfies the standard code most is selected for field application [61]. Again, increasing the surface roughness can effectively improve the performance of adhesives in the hygrothermal environment by increasing the effective connective area of concrete and adhesive [64].

2.2. Concrete substrate

Usually, the expected Fractures (mode I) occur within a few millimeters of the concrete surface [65–67]. The strength of the concrete substrate affects the debonding mechanism of the FRP-Concrete bond [68]. The strength of this concrete substrate is susceptible to temperature and humidity. Bazant et al. [69] found that concrete’s fracture energy (mode I) depends significantly on the temperature and has an inverse relationship with increasing temperature. They found this dependency more prominent in concrete having near-saturated water content than in pre-dried concrete. Again, Kallel et al. [70] investigated the tensile strength of concrete for five different levels of degree of liquid water saturation (Sw) for both 30℃ and 90℃ temperatures. It has been reported that the tensile strength has decreased with temperatures between 30℃ and 90℃. In contrast, it has increased for Sw between 36% and 72%. Again, high-strength concrete has been reported to have more sensitivity compared to low-strength concrete at elevated temperatures [71]. In general, humidity alone is not detrimental to concrete as it helps continue the hydration process of concrete, improving the concrete substrate’s strength [62]. But it sometimes initiates corrosive action by ingressing corrosive agents (like chlorides, sulfate, etc.) into the concrete. Besides, freeze–thaw action results in a volume change of water, which sometimes causes deterioration of concrete surface cum concrete substrate strength [72].

3. Hygrothermal effect on the combined system of FRP-Concrete bond

Five major test setups exist for studying the externally bonded FRP-Concrete bond [73]. A good number of researchers studied the hygrothermal effect on the combined system of FRP-Concrete bond using the setups mentioned above. Their research can be categorized into three types. The first type deals only with the effect of the temperature, whereas the second type deals with the effect of the humidity alone. But, the third type deals with both. A brief review of their works will be presented next.

3.1. Temperature

The FRP-Concrete bond strength decreases significantly above the applied adhesive’s glass transition temperature (Tg) and increases otherwise except for very low temperatures [74]. The high difference in the coefficient of expansion of bonding elements is believed to have mainly been responsible for the alternation of the behavior at low temperatures. The failure mode of bonding also changes from cohesive (into the concrete substrate) to decohesive (into the adhesive) with increasing temperature [52,75], see Fig. 1. The formation of microcracks in the FRP-Concrete bond is reported to have responsible for degrading bond strength at high temperatures [76]. Silva et al. [40] studied the effect of thermal cycles on specimens having gone through Freeze-thaw cycles for 1000 h. They found the bond strength has reduced by 31%. Again, Klamer and Hordijk [32] found an inverse relationship of bond strength with increasing temperature. They have also found the influence of temperature on the failure types of bonding. Kastro and Kim [77] found that the dry shear strength decreased less rapidly than the wet shear strength at high temperatures. Again, the usual practice of curing adhesive is at room temperature. According to Ferrier et al. [78], any change in the curing temperature (either increase or decrease) in the service life causes degradation in the bond strength. Table 1 shows the effects of temperature on different test methods for FRP and concrete specimens and other factors that affect test results. From Table 1, double shear [52,78] and direct tension [76] test experimental results show that minimum bond strength was found when the test specimen was at a higher temperature (for the direct tension test, the highest temperature reported was 240°C & for the double shear test, 80°C & 120°C). Most of the test results in Table 1 show that the maximum bond strengths were reported near 20°C, which is about room temperature [52,76,78]. However, in the double shear test method [52,78], there was no increase in strength below 20°C (room temperature), not even below freezing temperature (reported temperatures of −20°C and −40°C). On the other hand, minimum values are always shown when the test specimen temperature is higher. The findings of the subsequent tests [40,52,76] demonstrate that the method of the test and the layup procedure (whether wet or pultruded laminate) do not influence the bond strength. The sole factor that affects the strength’s increase and reduction is the temperature, which has already been mentioned above.

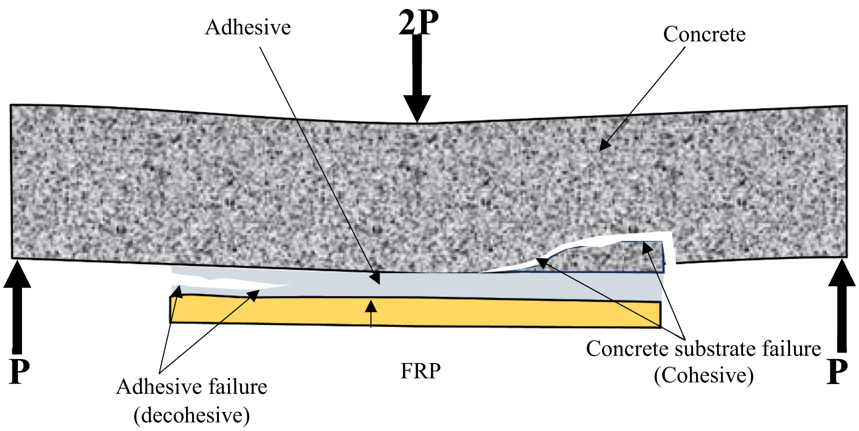

Fig. 1. Failure within the concrete substrate and the adhesive.

Table 1
The temperature effect on FRP-Concrete bond.

Test Method	Sample Type	Bond Strength (MPa) or Ultimate Load (kN)				T_g (°C)	f_c' (MPa)	Adhesive Properties		FRP Properties		
		Maximum (Temp., FM)	Minimum (Temp., FM)	Temperature range (°C)	Time Duration			T_s (MPa)	E (GPa)	T_s (GPa)	E (GPa)	t_p (mm)
DS [52]	wet layup process	3.15 (40, C)	0.91 (80, A)	−40°C to 80°C	–	76	–	20	3.2	0.825	97	–
	pultruded laminates	2.52 (20, C)	0.09 (120, A)	−20°C to 120°C		58		29.5	4.94	2.9	160	
DT [76]	wet layup process	2.5 (19, C)	2.54 (80, C)	19°C to 240°C	1.5 h	65	35.1^{28d}	48.03	2.58	4.154	210	0.19
			2.02 (160, C)									
			1.77 (240, C)									
			2.37 (80, C)		3 h							
			1.95 (160, C)									
			1.73 (240, C)									
		3.85 (19, C)	3.09 (80, C)		1.5 h		55^{28d}					
			2.76 (160, C)									
			2.57 (240, C)									
			2.87 (80, C)		3 h							
			2.58 (160, C)									
			2.18 (240, C)									
DS [78]	wet layup process	29.7^U(20, C)	9.05^U(80, A)	−40°C to 80°C	–	76	34 ± 2.5	20	3.2	0.825	97	0.05
	adhesive bonding technique	25.2^U(20, C)	0.9^U(120, A)	−20°C to 120°C		90		29.5	4.94	2.9	160	1.2

Note: SS = Single shear type test; DS = Double shear type test; B = Bending type test; MM = Concept of a mixed-mode loading test; DT = Direct tension type test; U = Ultimate Load Capacity (kN); FM = Failure Mode; C = Failure at concrete layer; A = Failure at Adhesive; T_g = Glass transition temperature; f_c'=Concrete Strength; T_S = Tensile Strength.

Also, in Table 1, it is evident that the concrete substrate failure mode is visible when the specimen temperature is less than the glass transition temperature. Both types of failure mechanisms were observed at temperatures above the transition point: concrete substrate failure and adhesive failure. In Table 1, the failure frequency of concrete substrate is comparatively higher than that of adhesive failure. Finally, two distinct temperature duration (1.5 and 3 h) effects are presented in this table. Three-hour-duration 240-degree centigrade specimens perform worse than room temperature conditions. In addition, there is no evidence of linear degradation in their test results (Fig. 2).

3.2. Moisture/Humidity

The effect of moisture is critical in the bond behavior of the FRP-Concrete interface [79]. As moisture contributes significantly to degrading the bond strength and fracture energy of FRP application [80–83]. Ouyang [34] portrayed the variation of interfacial fracture energy under a moist environment for two sets of samples (sets A & B) having two different concrete strengths (See Fig. 3). Alternation of adhesive property (see 2.1) in a humid environment is believed to have been responsible for this degradation [84]. Approximately 63% reduction of fracture toughness was observed in a particular set of FRP-

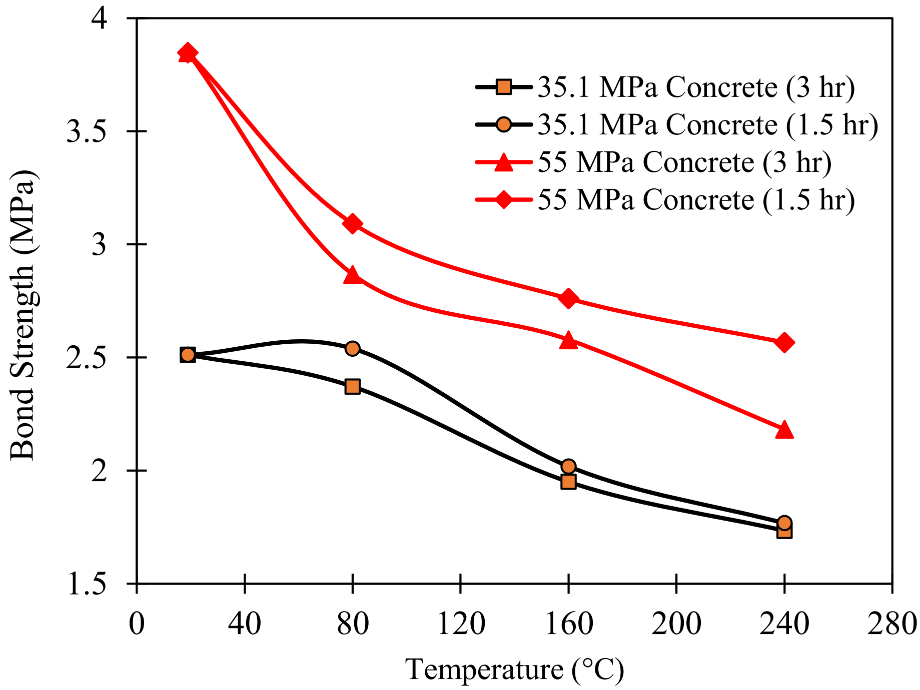

Fig. 2. Bond Strength (MPa) vs Temperature (°C) in a direct tension test over various durations. [76]

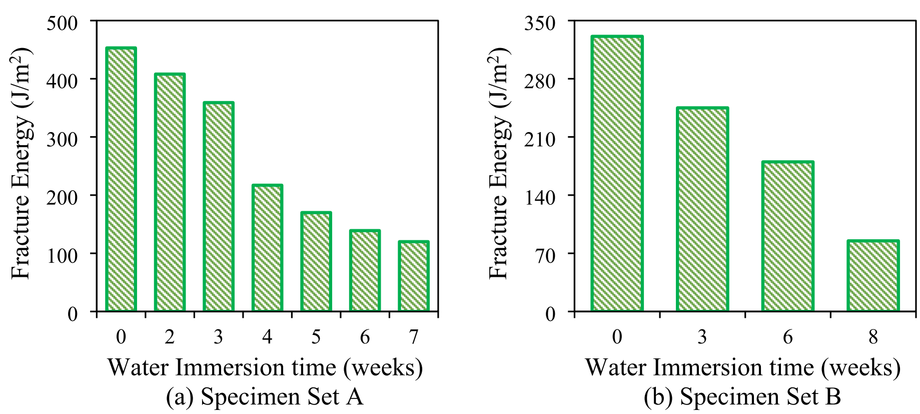

Fig. 3. Profile of interfacial fracture energy with respect to moisture exposure (immersion) duration [34].

Concrete bonds under predominantly water exposure for a duration of 8 (eight) weeks [85]. This degradation has been reported to increase up to 77% when moisture exposure is coupled with sustained load [86]. Again, Under a moist environment for 120 days, a 40% reduction of the flexural capacity of a particular FRP application is reported by Karbhari and Zhao [87]. The alternate wet-dry cycle is also reportedly responsible for decreasing the bond strength of the FRP-Concrete bond [88]. For specimens subjected to frequent wet/dry cycles, the bond failure occurs at the interface between the primer and concrete surface rather than in the concrete substrate [89]. Shrestha et al. [90] found that moisture effects depend on the types of FRP systems. For example, Bond strength decreases for wet-layup FRP, whereas it increases for prefabricated FRP under sustained moisture. This observation is also supported by the research done by Abanilla et al. [35]. Tamon et al. [91] commented that softer resin at the interface due to continuous moisture/or immersion is presumably responsible for bond strength increase in both FRP systems. However, the tendency of wet-layup FRP under moisture exposure to have failure in (resin-concrete) adhesion rather than in concrete substrate makes its bond strength decreasing in prolonged moisture exposure [92]. Again, bonding at the FRP-Concrete interface is a result of both chemical and mechanical adhesion [93]. Chemical adhesion is greatly affected by moisture, whereas mechanical adhesion depends on surface roughness. Therefore, FRP-Concrete bonding with lower surface roughness shows a significant decrease in bond strength under moisture exposure. On the contrary, the bonding with higher surface roughness shows an insignificant decrease in bond strength under moisture exposure [92]. Besides, the extent of degradation due to moisture is greatly varied for material properties and specimen configuration [94]. Excess moisture is also responsible for degrading the fatigue performance of the bonded connection [63].

Local debonding of the FRP-Concrete interface can also be caused by vapor and osmotic pressure resulting from induced moisture [34]. As a result, the presence of water/ moisture at the concrete substrate level causes degradation of bonding between FRP and substrate [84]. Pan et al. [95] reported that the bond between concrete silica and adhesive significantly deteriorated under a humid environment, which in turn, was responsible for shifting the failure from the concrete substrate to the adhesive. Again, the merely moist concrete substrate is reported to be more detrimental in terms of bonding strength compared to a completely saturated concrete substrate [96]. There is very limited study on the initial bond performance of FRP-to-concrete interfaces due to moisture presence. According to Myers and Ekenel [97], the maximum recommended values of the air relative humidity (RH), the concrete surface moisture content, and the air temperature are 82%, 4.3%, and 30.5℃, respectively. In Table 2, the moisture effect on FRP, the Single Shear Test [95], Double Shear Test [94], Bending Test [40,89], and Mixed Mode Test [34] are shown. A bend test in salt fog conditions was performed on GFRP and CFRP [40]. The test lasted from 0 to 10,000 h (417 days), and maximum capacity was discovered in CFRP at the initial condition but in GFRP after 5,000 h. Capacity increases in salt fog conditions in GFRP due to temperature and curing effects. Another two types of test are performed on GFRP, full immersion in water and −10℃ to 10℃ temperature cycles of similar duration as salt fog conditions. From those two considerations (full immersion and temperature cycle), the maximum capacity was found after a 1000 h test, and the capacity decreased by 21% and 31%, respectively, after 10,000 h. The temperature cycles affect more severely in GFRP among the three tests. Failure behavior in salt fog tests in GFRP and CFRP showed adhesive failure and the remaining consideration showed concrete substrate failure mode.

Another bending type test is described in Table 2, due to 48% relative humidity environmental conditions [89]. Due to the long duration required for curing purposes, the Carbon Strand Sheet (CSS) procedure is used in this test, and the wet layup process is not considered here. Two

Table 2
The moisture effect on FRP-Concrete bond.

Test Method	Sample Type	Condition	Bond Strength (MPa) or Ultimate Load (kN)			T_g (°C)	f'_c(MPa)	Adhesive Properties		FRP Properties		
			Maximum (Day, FM)	Minimum (Day, FM)	Test Duration (Day)			T_s (MPa)	E (GPa)	T_s (GPa)	E (GPa)	t_p (mm)
B [40]	GFRP, wet layup Process (Control specimen bond stress 3.71 MPa)	Salt fog (35°C dry 16 h & 8 h fog)	4.73 (208, A)	4.09 (417, A)	0, 42, 208 & 417	82	47 ± 2.4	72.4	3.18	0.5	20.4	1.3
		Temperature cycles (-10°C for 12 h; 10°C for another 12 h)	3.45 (42, C)	3.14 (417, C)								
		Immersion	4.92 (42, C)	4.32 (417, C)								
	CFRP (Control specimen load capacity 34.0^U kN)	Moisture Cycle (RH = 20% for 12 h and RH = 90% for another 12 h)	34.9^U (417, C)	31.0^U (250, C)	0, 125, 250 & 417	71	32.7 ± 0.6	54	3.034	3.937	241	0.176
		Salt fog (Same as GFRP)	34.0^U (0, A)	29.2^U (250, A)								
MM [34]	Precured CFRP Laminate	Specimen Prepared at Room temperature and RH = 30–40%. Water bath temperature = 23°C	3.10 (0, C)	1.74 (56, C)	0, 21, 28, 42 & 56	NA	28^{28d}	72.4	3.18	2.02	139	2
	Hand-layup unidirectional carbon fiber sheet	Specimen Prepared at Room temperature and RH = 40–50%. Water bath temperature = 23°C	2.66 (0, C)	1.43 (56, C)	0, 21, 28, 42 & 56		43^{28d}			–	72.5	3
B [89]	CFRP, Carbon Strand Sheet (CSS)	Primer FP-WE7, Adhesive CN-100 & RH = 48%	27.7^U (0, A)	21.6^U (56, F), 21.4^U (98, F), 14.3^U (168, A)	0, 56, 98, 168	NA	33.7	NA	0.39	greater than3.4	245	0.178
		Primer FP-WE7, Adhesive FE-Z & RH = 48%	24.3^U (0, C)	22.6^U (56, F), 19.9^U (98, F), 20.2^U (168, F)	0, 56, 98, 168	60		NA	2.41			
		Primer FP-NS, Adhesive FE-Z & RH = 48%	19.5^U (0, C)	18.7^U (56, F), 19.9^U (98, F), 15.7^U (168, F)								
DS [94]	CFRP, wet layup	Full Immersion & Temperature 23°C	2.88 (0, -)	2.01 (175, -)	0, 56, 175	NA	31	44.3	2.95	2.319	198.84	–
SS [95]	CFRP, pultrusion process, Full Immersion	1 mm adhesive layer & temperature 20°C	8.8 (0, C)	6.2 (56, A)	0, 14, 28, 42, 56	65.7	37.4	57.1	3.2	1.8	150.8	1.3
		0.2 mm adhesive layer & temperature 20°C	10.87 (0, C)	6.23 (42, A)	0, 14, 28, 42							
		1 mm adhesive layer & temperature 50°C	8.76 (0, C)	7.3 (14, A)	0, 14							

Note: SS = Single shear type test; DS = Double shear type test; B = Bending type test; MM = Concept of a mixed-mode loading test; DT = Direct tension type test; U = Ultimate Load Capacity (kN); FM = Failure Mode; C = Failure at concrete layer; A = Failure at Adhesive; F = primer-to-concrete interface failure; T_g = Glass transition temperature; f'_c=Concrete Strength; T_S = Tensile Strength.

new primers, FP-WE7 and FP-NS, and two new epoxy putties, CN-100 and FE-Z, were used. The CN-100 is less elastic than FE-z putty. In all conditions, maximum capacity was found in the initial state and, in most cases, minimum capacity was found after 24 weeks of aging. CSS specimen tests three types of failure modes in this CFRP: observed concrete substrate, adhesive, and primer-to-concrete interface failure.

Finally, a similar trend was found among the multi-mode [34], single-shear [95], and double-shear tests [94]. In all three conditions, the maximum capacity was stated in the initial situation, and the minimum one at the end (when the test duration was completed) of the test was found. The failure mode of the concrete substrate was mostly observed in multimode (all conditions) and single-shear tests (initially observed). But in the full immersion single-shear test, an adhesive failure mode was also observed at the end of the test. During a single-shear test in dry conditions, a thinner adhesive layer shows a higher load capacity than a thicker layer. When the specimen is completely submerged in water, the thickness of the adhesive layer doesn't matter as much as it did when the specimen was completely dry.

3.3. Hygrothermal

Tamon et al. [93] found that the hygrothermal effect is less on the rougher concrete subsurface. They also found that the effect of moisture change is more compared to temperature change on FRP-Concrete bonding. The worst effects were found under both full immersion and freeze-thaw cycles. Again, on the contrary, Crastro and kim [77] found that for the freeze-thaw cycle ranging from −5℃ to 20℃ along with very a humid environment resulted in increase in double shear lap strength. Datla et al. [98] found that the degrading effect due to the combination of low relative humidity (0%) and high temperature (100℃) on the FRP-Concrete bond is more severe than the combined effect of the high temperature (100℃) and the high relative humidity (100%).

Zheng et al. [99] studied the fatigue performance of FRP-Concrete bond having specific hygrothermal pre-treatment (RH = 95%, T = 60℃). They found the fatigue life has decreased by approximately 23% at the maximum applied load (80% of the static load capacity). Reduction of the ductile behavior and the increase of the force-transferring region in the Carbon Fiber laminate (CFL), applied on the test specimens, were also reported in their study. Qin et al. [100] also found a decrease of fatigue limit of the studied specimens under increasing temperature and moisture. They further studied the samples coupled with the hygrothermal environment and the sustained loading. Their coupled specimens fatigue limit was found 20% less than the uncoupled specimens. Kabir et al. [101] kept their specimens in the outdoor environment of Sydney and found bond strength decreased by 15% after six months. After this period an increasing trend has been reported which reached an equilibrium state after one year of exposure to the outdoor environment. In another study, the interface fracture toughness of epoxy/concrete bond is reported to have reduced by about 50% under selective hygrothermal environment and mode conditions [102]. The strain energy release rate of the FRP to concrete bond subjected to a particular hygrothermal exposure (T-100℃ & RH- 95%) is reportedly less than the samples under normal laboratory exposure [103]. Mikami et al. [41] investigate the hygrothermal effect of FRP bonded concrete at room temperature and two different exposure temperatures (100℃ and 180℃). Throughout the entire test, two relative humidity (0% and 100%) conditions are applied constantly, except for the room temperature (RH = 25%) condition. Their test results bond strength varied from 6.27 MPa to 0.5 MPa for three different numbers (40, 100, 250) of cycle tests. From their test results, they declare that at room temperature, bond strength is higher than 6 MPa, which is adequate for most engineering applications. They also noticed the combination of high temperature (100℃ and 180℃) and low humidity (RH = 0%) is the most detrimental to bond strength because bond strength decreased by 92% (180℃, 0%) and 50.6% (100℃, 0%) compared to the initial condition. On the other hand, the presence of moisture (RH = 100%) and higher temperature exposure were beneficial to the bonding between concrete and FRP because bond strength decreased by 27.4% (180℃, 100%) and 20.3% (100℃, 100%) compared to the initial condition, which decreased less than dry (RH = 0%) conditions and high temperatures (100℃ and 180℃). Finally, they assert that cross-linking of epoxy resin helps to increase initial strength. For this reason, 180℃ (0% and 100%) temperature shows an increasing manner up to 100 cycles, then decreases to 250 cycles. In another research group [43] research findings, a proportional relationship was observed at a 60℃ temperature with three different moisture contents, which are 60%, 75%, and 95%, and their bond strength decreases by 15.1%, 18.7%, and 28%, respectively, when compared to room temperature. Another proportional relationship discovered in their research is that a constant moisture content of 95% was applied in three different specimens at three different temperatures, 5, 25, and 60℃ and their bond strength decreased by 16%, 24%, and 28%, respectively, to their room temperature. They mention also that the bond strength would decrease by 24% in comparison to room conditions if the specimen temperature was slightly increased from room temperature 23°C to 25°C and the moisture content increased from 65% to 95%. Both results indicate a significant impact of the moisture content on the strength of the bond. The abovementioned two research groups explored hygrothermal impacts on FRP using two distinct test methods: the double shear test [43] and the direct tension test [41], and their reported results are aggregated in Table 3.

4. Performance of FRP laminates versus FRP fabrics under hygrothermal environment

CFRP laminates are produced through a process called pultrusion, where FRP is continuously molded in a thermosetting resin matrix [104]. For CFRP fabric, the production process is somewhat similar to laminate which involves bonding fibrous materials with a suitable matrix during molding [105]. But the resulting fabric is usually thinner than laminate. Though both the laminate and the fabric have been used for strengthening purposes, laminate is widely accepted for large structures for having high strength and fewer defects. However, several studies have been carried out to compare the performance of the FRP laminates and the FRP sheet (fabric) in a hygrothermal environment. Grace and Singh [106] studied the performance of both FRP laminate and sheets for different harsh exposures (for 10,000 h). It has been found that the bond strength has been reduced by 32% and 10% for FRP laminates and fabrics (sheets), respectively (RH = 100%, T= 40℃). Again Dolan et al. [107] studied the hygrothermal performance of strengthened beams using both FRP laminates and fabrics. They found even at moderate temperature (30℃) and submerged condition, the specimens strengthened by laminates, have shown a reduction of bond strength by 60% in beam testing. In contrast, there is almost no reduction in fabrics. Karbahri and Ghosh [108] studied laminates and fabrics through pull-out tests under hygrothermal exposure accompanied by salt immersion. They found the overall performance of the laminates is poorer than fabrics. But laminates are found to perform better than fabric for dried high temperature alone [109]. The thicker layer of adhesive is more susceptible to the hygrothermal environment. The fact that the application of the laminate requires a thicker layer of adhesive compared to the FRP sheet might be the reason for its poorer bond performance compared to the FRP sheet [42].

5. Modeling of FRP-Concrete bond with and without hygrothermal effects

Previous analytical models of FRP-Concrete bond primarily consider the gross bond area as the varying parameter [110,111]. The later models started to consider other aspects like the stiffness of FRP sheet [112], fracture mechanism of concrete [113–115], effective bond length [67,116–118], etc., hence giving better prediction on the FRP-Concrete

Table 3
The hygrothermal effect on FRP-Concrete bond.

Test Method	f_c'(MPa)	Fiber Reinforced Polymer			T_g (°C)	Bond Strength (MPa)		MC%	T_{test} (°C)	Test time	E_{ep} (GPa)
		E (GPa)	T_s (GPa)	t_p (mm)		Minimum	Maximum				
DT [41]	38	230	3.45	0.5	82	$5.7^{b,c1}$, $3.1^{d1,c1,a}$, $4.5^{d1,c3,c}$, $0.5^{d2,c3,a}$, $1.77^{d2,c3,c}$	$6.26^{b,c3}$, $3.9^{d1,c3,a}$, $5^{d1,c1,c}$, $1.87^{d2,c2,a}$, $4.55^{d2,c2,c}$	0^a, 25^b, 100^c	25^b, 100^{d1}, 180^{d2}	80^{c1}, 200^{c2}, $500^{c3,h}$	3.18
DS [43]	35.4	220	4.03	0.23	85	$0.648^{t3,r3}$, $0.684^{t2,r3}$, $0.732^{t3,r2}$, $0.756^{t1,r3}$, $0.764^{t3,r1}$	0.9^b	60^{r1}, 65^b, 75^{r2}, 95^{r3}	5^{t1}, 23^b, 25^{t2}, 60^{t3}	14^D	2.5

Note: SS = Single shear type test; DS = Double shear type test; B = Bending type test; MM = Concept of a mixed-mode loading test; DT = Direct tension type test; MC = Moisture Content; f_c'= Concrete Strength;T_{test} = Temperature at test condition; T_s = Test Condition; T_s = FRP Tensile Strength; t_p = FRP thickness; E_{ep} = Elastic Modulus of Epoxy; Ad = Adhesive; a = oven condition; b = room temperature/ Lab condition; c = immersion condition; d1 = condition 1; d2 = condition 2; c1 = 40 cycle test; c2 = 100 cycle test; c3 = 250 cycle test; h = hours; D = days;W = weeks; M = months; Ga = Group-A uncoupling action of hot-wet environment; Gb = Group-B coupling action of hot-wet environment; Gc = Group-C coupling action of hot-wet environment; t1 = temperature condition-1; t2 = temperature condition-2; t3 = temperature condition-3; r1 = relative humidity condition-1; r2 = relative humidity condition-2; r3 = relative humidity condition-3.

bond strength [67]. In this section, the performance of some proposed models is evaluated. In Table 4, the proposed models are presented chronologically to portray the changes over time. The earliest model [119] only considered concrete substrate tensile strength (f_{ctm}) for determining the delamination load (P_u). The shear stress in the bonded area is assumed triangular in this model. The model presented in [112] introduced the concept of effective bond length (L_e). Later models [120–123] considered the effect of FRP strip width (b_f) and concrete prism width (b_c) by a width effect correction factor (β_ω). However, the model in [124] considered the effective bond length (L_e) independent of concrete substrate strength (f_{ctm}). The model in [125] considered the non-linearity of shear stress (τ_a). Again, the fracture energy (G_f) concept is introduced in [113] and later used with other parameters in [126,127]. The model in [128] used both the fracture energy (G_f) and the width correction factor (β_ω) to calculate the delamination load (P_u). The database presented in Lu et al.'s [129] work has been used to calculate the predicted delamination load (P_u) using the models mentioned above. The predicted values are compared with experimental values to evaluate the performance of the proposed models.

Before picking any model for better prediction, it is necessary to establish a few criteria for determining whether or not any analytical model is eligible for consideration. Generally, the coefficient of determination (CoD) score should be close to 1, but a higher CoD value does not always suggest that the model is well-fitted. The 95% confidence interval (CI) band of a linear model is regarded to be sufficiently fit when it is closer to the dispersed data and has an appropriate CoD score, according to Barrett et al. [130]. It is important to note that any model with a negative CoD score indicates that it is poorly fitted in the experimental linear relationship model. Fig. 4 (k) illustrates a shorter 95% confidence interval band, but because the model CoD score is negative, it is not considered to be a statistical correlation by the statistical establishment. Three models in Fig. 4 (d, g, and j) have CoD scores of more than 0.6, and the 95% confidence intervals are more closely fitted. Therefore, these models can be considered to perform well. Fig. 4 (d) and (j) show better statistical correlation than Fig. 4 (g) as the latter only considers the effective bond length. In contrast, the formers consider both the effective bond length (L_e) and the width correction factor (β_ω) in evaluating delamination load (P_u). Again, Fig. 4 (d) shows a better statistical correlation than Fig. 4 (j). The better performance of the model in Fig. 4 (d) can be attributed to the better calibration of the experimental values in the model while developing the model [131].

Besides the analytical approach, the literature widely reports the numerical models of FRP-Concrete bond. The numerical model can be divided into three categories, namely, the direct modeling approach [132,133], the interface model approach [66], and the crack band approach [134,135]. The approaches are different regarding the presence of interfacial elements and variation of properties of concrete near the crack zone. The direct modeling approach considers the direct connection between concrete and FRP element. Hence there is no interfacial element (like adhesive) between the FRP-Concrete bond. In contrast, the interface model approach considers an interfacial element between the FRP-Concrete bond. The crack band approach is somewhat similar to the interface model approach, except it considers modified properties of concrete near the bonding interface than the concrete away from the interface. The graphical form of the discussed approaches with their salient characters is presented in Fig. 5.

To summarize, the direct modeling approach is the best predictive approach but is less common due to the challenges associated with modeling using this approach. Again, the interface model approach is common due to its simplicity. Discrete and smeared models are commonly used to model concrete fracture in the above-mentioned numerical approaches. But, there are several studies where both crack band approaches have been used [136,137]. In those studies, the smeared crack model has been used for minor cracks, whereas the discrete crack model has been primarily used for major cracks. In general, the smeared crack model is preferable over the discrete crack model because of its independence from predefining the crack locations. But the smeared crack model is sensitive to finite element meshing due to strain softening, and this drawback can be overcome by defining fracture energy independent of element size [133,138,139]. The following paragraphs will represent some of the works of different researchers on modeling FRP bonding subjected to temperature and humidity together and individually.

The modeling of the temperature and the humidity-induced FRP-Concrete bond is simply an extension of standard FRP-Concrete bond modeling, where the extended part accounts for the effect of temperature and humidity. This extended part usually involves developing a bond model considering the effect of the above-mentioned parameters. There are very few researchers who deal with this kind of model development. Yanchun [140] formulated a bond-slip relationship considering the freeze–thaw cycles. Again, Dai [141] developed a bond-slip model considering the elevated temperature. The two parameters used for evaluating this model are the interfacial brittleness index (B) and the interfacial fracture energy (Gf). Similarly, Arruda et al. [142] developed a numerical model of FRP-Concrete bond subjected to high temperature. In their model, some bi-linear bond–slip laws have been used to simulate the interface behavior at elevated temperatures. The bilinear bond-slip laws were initially developed based on the FRP-

Table 4
Analytical models for predicting the strength of the connection between FRP and concrete.

Sl. No.	Ref.	Year	Equation	Coefficient of Determination (CoD)
(a)	[119]	1980	$P_u = 0.5 b_f L f_{ctm}$	0.129
(b)	[113]	1994	$P_u = b_f\sqrt{E_f t_f G_f}$ *where :* $G_f = c_f f_{ctm}$ *with* $c_f = 0.204\ mm$	0.485
(c)	[112]	1997	$P_u = \tau_a b_f L_e$ *where :* $L_e = e^{\left[6.13-0.58ln\left(E_f t_f\right)\right]},\ \tau_a = 110.2\times10^{-6}E_f t_f$	−0.454
(d)	[120]	2001	$P_u = \begin{cases} 0.427\beta_\omega b_f L_e\sqrt{f_c} & when\ L\geq L_e \\ 0.427\beta_\omega b_f L_e\sqrt{f_c}\,sin\left(\frac{\pi L}{2Le}\right) & when\ L<L_e \end{cases}$ *where :* $L_e = \sqrt{\frac{E_f t_f}{\sqrt{f_C}}},\ \beta_\omega = \sqrt{\frac{2-\frac{b_f}{b_c}}{1+\frac{b_f}{b_c}}}$	0.885
(e)	[121]	2001	$P_u = \begin{cases} 0.64\alpha\beta_\omega b_f k_c\sqrt{E_f t_f f_{ctm}} & when\ L\geq L_e \\ 0.64\alpha\beta_\omega b_f k_c\sqrt{E_f t_f f_{ctm}}\ \frac{L}{L_e}\left(2-\frac{L}{L_e}\right) & when\ L<L_e \end{cases}$ *where :* $\beta_\omega = 1.06\sqrt{\frac{2-\frac{b_f}{b_c}}{1+\frac{b_f}{400}}},\ L_e = \sqrt{\frac{E_f t_f}{2f_{ctm}}}$ *with* $\alpha = 1$ *and* $k_c = 1$	0.504
(f)	[124]	2001	$P_u = (0.5+0.08\sqrt{\frac{E_f t_f}{100 f_{ctm}}})\tau_a b_f L_e$ *where :* $\tau_a = 0.5 f_{ctm},\ L_e = 100\ mm$	−1.438
(g)	[125]	2003	$P_u = \tau_a b_f L_e$ *where :* $L_e = 0.125\left(E_f t_f\right)^{0.57},\ \tau_a = 0.93 f_c^{0.44}$	0.692
(h)	[126]	2004	$P_u = b_f\sqrt{2E_f t_f G_f} = b_f\sqrt{2\frac{f_{ctm}}{8}E_f t_f} = 0.5 b_f\sqrt{E_f t_f f_{ctm}}$ *where :* $G_f = \frac{f_{ctm}}{8}$	−0.649
(i)	[127]	2005	$P_u = \begin{cases} b_f\sqrt{2E_f t_f G_f} & when\ b_f<100mm \\ \left(b_f+2\Delta b_f\right)\sqrt{2E_f t_f G_f} & when\ b_f\geq 100mm \end{cases}$ *where :* $G_f = 0.514 f_c^{0.236},\ \Delta b_f = 3.7\ mm$	0.350
(j)	[122]	2009	$P_u = \begin{cases} 0.585 b_f\beta_\omega f_c^{0.1}\left(E_f t_f\right)^{0.54} & when\ L\geq L_e \\ 0.585 b_f\beta_\omega f_c^{0.1}\left(E_f t_f\right)^{0.54}\left(\frac{L}{L_e}\right)^{1.2} & when\ L<L_e \end{cases}$ *where :* $\beta_\omega = \sqrt{\frac{2.25-\frac{b_f}{b_c}}{1.25+\frac{b_f}{b_c}}},\ L_e = \frac{0.395\left(E_f t_f\right)^{0.54}}{f_c^{0.09}}$	0.773
(k)	[128]	2010	$P_u = \beta_\omega b_f\sqrt{2(1+\frac{\lambda'}{\Sigma})E_f t_f G_{cf}}$ *where :* $\beta_\omega = \sqrt{\frac{2-\frac{b_f}{b_c}}{1+\frac{b_f}{b_c}}},\ \lambda' = \frac{t_d}{t_f}$ *with* $t_d = 3.5\ mm,\ \Sigma = \frac{E_f}{E_c},\ G_{cf} = 0.17\frac{N}{mm}$	−1.05
(l)	[123]	2012	$P_u = 0.5 b_f\beta_\omega\sqrt{E_f t_f f_{ctm}}$ *where :* $\beta_\omega = 1.06\sqrt{\frac{2-\frac{b_f}{b_c}}{1+\frac{b_f}{400}}}$	−1.308

Concrete bond test results at various temperatures and further calibrated through inverse analysis. The final bilinear bond-slip laws are bilinear lines presenting two distinct zones of bond-slip behavior for each setup and temperature (See Fig. 6).

Shrestha [90] developed a bond-slip behavior considering the moisture exposure effect. There, the moisture effect is considered by relating interfacial fracture energy (GI) and ductility index (B) with the duration of moisture exposure. This bond-slip behavior can be used for numerical modeling of FRP-Concrete bond subjected to moisture attack. Similarly, Tuakta [143] related the mechanical properties of the FRP

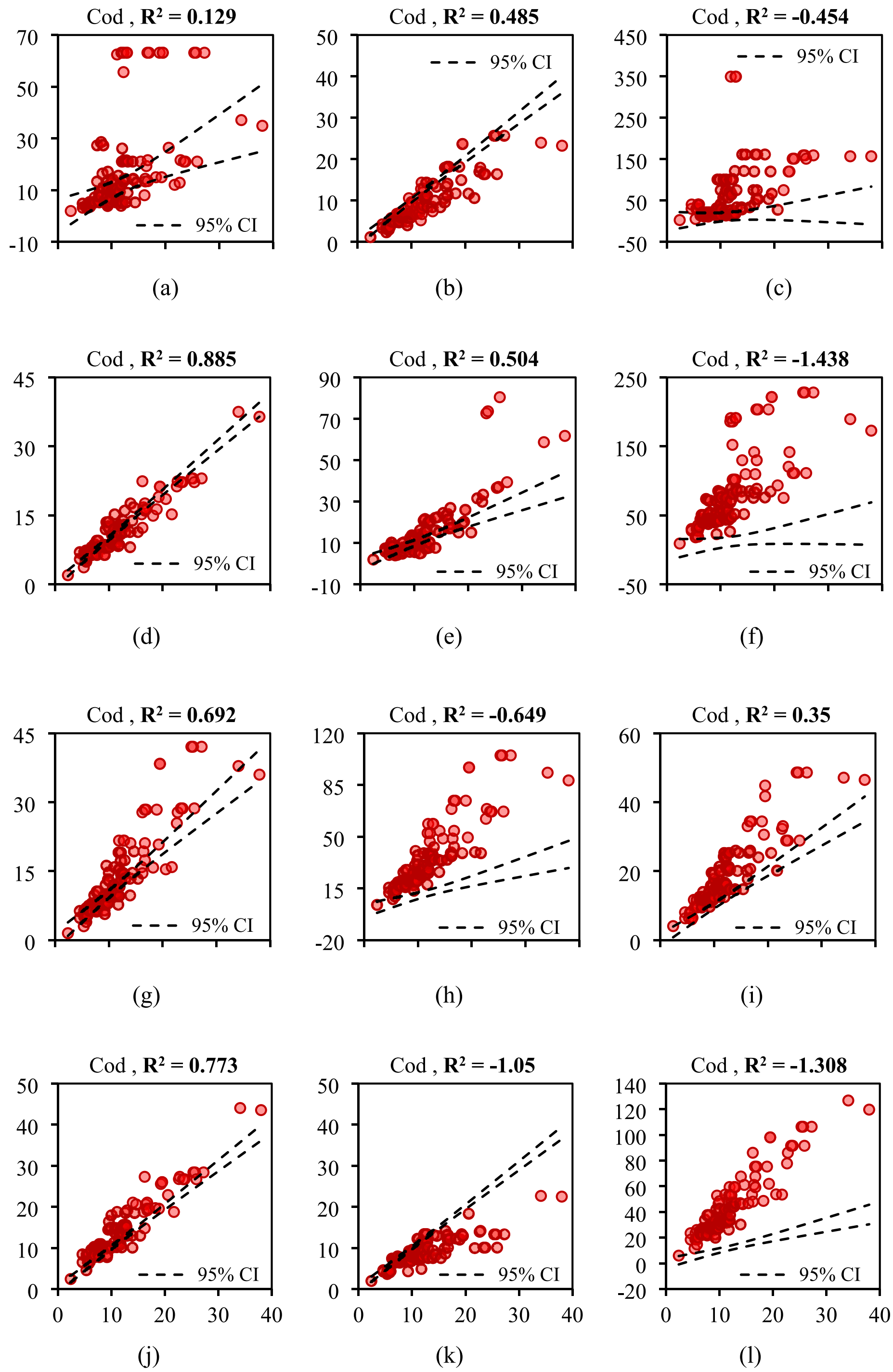

Fig. 4. Correlation between predicted and experimental data with a 95% Confidence Interval (CI).

composite element with moisture. These properties were used to develop a fracture-based Tri-layer model [143]. This model was used to study the deterioration of the FRP-Concrete bond under various moisture conditions. Zhou [86] developed a moisture-based degradation model. This model relates interfacial fracture toughness to the duration of moisture exposure. Ouyang et al. [34] correlated the bond fracture energy with the bond interface region relative humidity (IRRH) to develop a deterioration model of the bond interface. A relationship was determined with IRRH to the relative humidity of the environment and the environmental exposure time of the given specimen through moisture diffusion analysis. This deterioration model considered both absorption and interlocking mechanism. Finally, the debonding of FRP was simulated using a cohesive zone model [144].

Khoshbakht et al. [145] developed a formulation that deals with the transformation of heat and fluid through layered structures based on a theory prescribed by Philip and De Vries [146]. They modeled a typical FRP applied layered structure subjected to hygrothermal effect using the above-stated formulation and a commercially available finite element-based software, FEMLAB. Both isothermal and non-isothermal conditions were considered in the stated model. From analyses, it has been found that the humidity at the bond interface increases when the inside temperature is less than the outside temperature and vice versa. Again, the rapid change in the temperature at the bond interface results in a hike in relative humidity at the same place. Again, Heshmati [147]

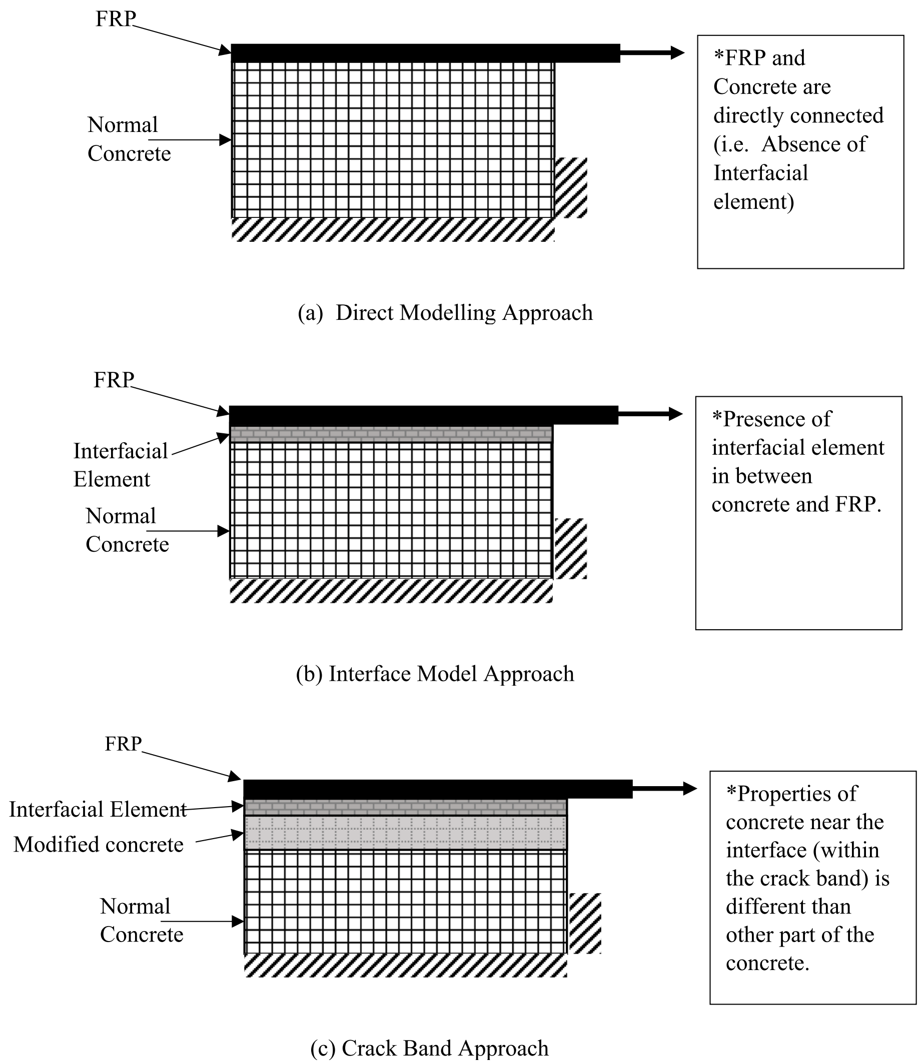

Fig. 5. Different Approach to Modelling FRP-Concrete Bond of a typical pull–push configuration.

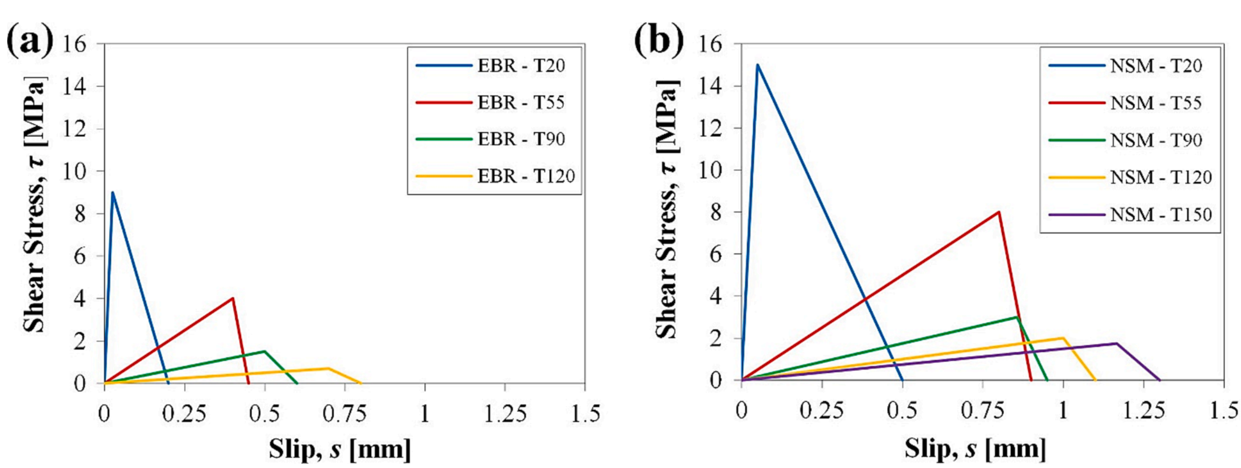

Fig. 6. Bilinear bond-slip laws for (a) EBR setup and (b) NSM setup [142].

related moisture diffusion as a function of temperature. Further, he characterized the moisture effect with the mechanical properties of adhesive and FRP materials. Finally, he used the above-mentioned relation and characterization to implement a coupled diffusion-mechanical finite element model using ABAQUS, a commercially available finite element-based software.

6. Discussions and salient issues

The FRP-Concrete bond can be attributed mainly to two things, namely mechanical interlocking and chemical adhesion [148]. Mechanical interlocking is believed to develop by solidifying the penetrated adhesive into the concrete layer. As a result, surface roughening is beneficial in increasing the bond capacity of the FRP application [107]. Besides, roughening gives a greater area for chemical bonding, hence increasing the FRP-Concrete bond. Still, chemical bonding is proved to be less susceptible than mechanical interlocking when the surface roughness is varied [93]. However, the mechanical interlock bond strength of an exposed (moisture) specimen is partially recoverable, whereas chemical adhesion is not [149–151]. But there is no available method to quantify the contribution of each parameter separately in hygrothermal exposure [107]. However, He et al. [64] developed a technique for quantifying the contribution of mechanical interlocking and chemical adhesion separately in immersion only. The technique considers only the water-cement ratio of concrete to develop mechanical interlocking contributions. Other aspects affecting mechanical interlocking, like surface preparation, are absent in their study. Further research can be carried out to consider those aspects and then quantify the contribution of mechanical interlocking and chemical adhesion separately in hygrothermal exposure.

The performance of the adhesive (in terms of stiffness) varies greatly above the glass transition temperature (Tg) of the adhesive (see 2.1). Since the performance of interlocking largely depends on the stiffness of the adhesive, the FRP-Concrete bond performance is supposed to degrade at a temperature higher than Tg. But due to the fact that the softer adhesive layer creates higher shear bonding reported by Dai et al. [24], things are not straightforward. So, further research is required to quantify the effects of temperature on FRP-Concrete bonding. Again, mechanical interlock degradation can also occur from the fracture of the adhesive zone [85] along with pull out from the interlocked surface (See Fig. 7).

But, until now, to the authors' knowledge, it is not possible to quantify their contributions separately. Further research can be conducted to address this issue. Again, the expected debonding is supposed to take place in the concrete substrate, but there are cases it happens in the adhesive layer or other interfaces or both at the same time [152]. This phenomenon usually occurs when an adhesive with a low Tg is used in the FRP-Concrete bond subjected to hygrothermal environment [153]. Enhance ingenuities should be carried out to ensure expected debonding into the concrete substrate, possibly by improving the quality of the adhesive to utilize the FRP strength effectively. This kind of premature bonding can also be controlled by furnishing surface treatment of concrete prisms [20,154] and by providing different kinds of anchorage systems [155–157] and FRP wraps [3,158]. Again, FRP laminate's performance is better than FRP fabric under all hygrothermal environments, except for very high temperatures accompanied by dry exposure. The inferior performance of laminates might be attributed to the thicker adhesive layer compared to fabrics which is more susceptible to hygrothermal environments. Further investigations are required for more clarification.

It was expected that higher temperatures would affect bond strength and reduce it from initial conditions. But this reduction does not happen linearly or proportionally in all temperature cases. For example, sometimes bond strength is found to be slightly higher than in initial conditions (room temperature) [76], but in most cases, the trend is a decrease in strength as temperature increases. Different temperature and

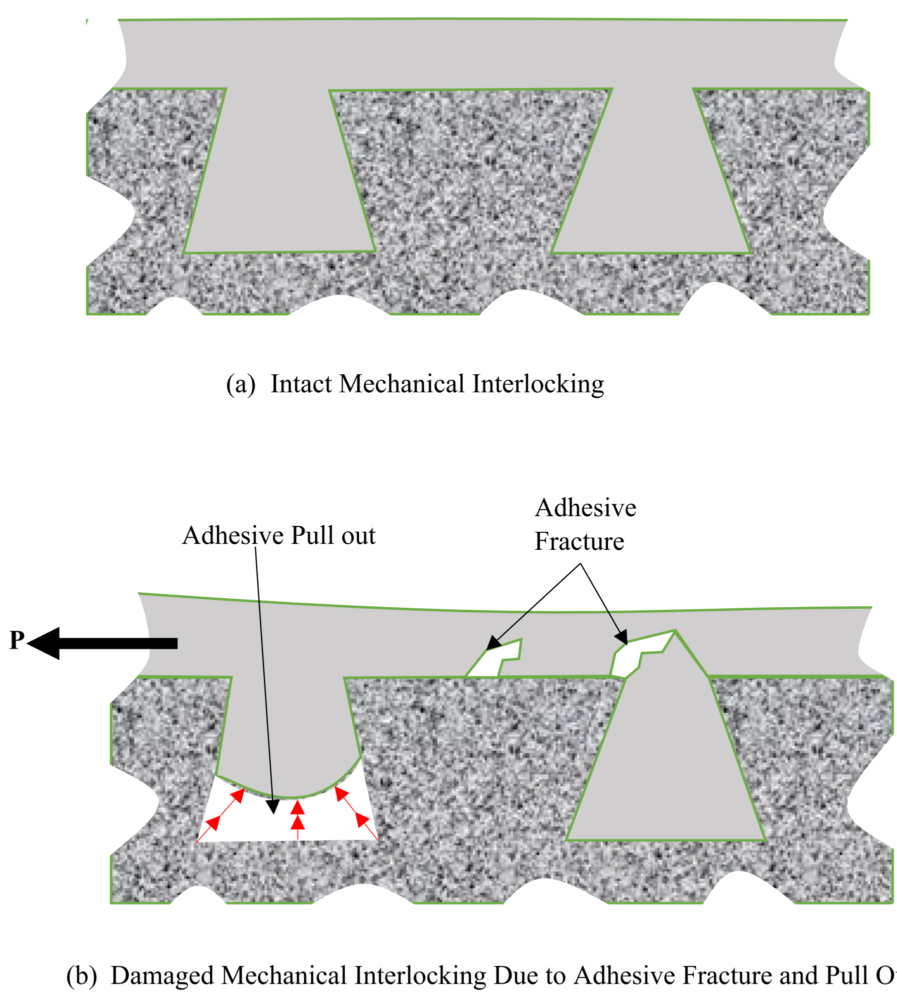

Fig. 7. Mechanism of Degradation of Mechanical Interlocking.

exposure time combinations need to be tested in the lab to characterize the bond strength behavior under different environmental exposure.

The analytical and numerical modeling of the FRP-Concrete bond gives better bond strength prediction under hygrothermal environments when the model considers the material properties changes due to environmental exposure. Few research works on analytical and numerical FRP-Concrete modeling are reported to have incorporated hygrothermal behavior in the bond models. This calls for the need to have more research works with sufficient details to boost the understanding of the topic. In addition, most of the common modeling approaches of FRP-Concrete bond described in Section 5 primarily consider failure in the concrete substrate. Though this is the most expected type [11,159], it is not the only type of failure. Bond failure can also occur within the adhesive, or in the interface between the adhesive and the concrete [160], or between the adhesive and FRP [29]. Failure in only one type of the aforementioned modes is highly improbable for a properly FRP strengthened structure. A combination of two or more of such modes is possible because of some uncertainties related to proper FRP application. Unaccounted environmental exposures like unusual heat, extreme humidity, etc., also add to these uncertainties. Further effort can be carried out to develop models that consider both adhesive failure and concrete failure at a time in a more realistic manner.

Almost all major test setups for studying FRP-Concrete bonds have been used for evaluating the hygrothermal effect on bond properties (See 3). But the bending or beam type test and the pull-off test are found to be comparatively prevalent over other test methods. Perhaps, the simplicity and user-friendliness of those set up are the reason for their extensive use. However, comparing bond strength using different test methods is difficult, even with the same environmental conditions, as the stress variation of the bonded area varies greatly depending on test methods [161,162]. Aiello and Leone [161] found bond stress eight times higher in some test set up compared to others. Another shortcoming of all the test setups is the absence of the hygrothermal environment during testing. The most common practice is to keep the test samples in the laboratory environment for adequate time to reach laboratory temperature and humidity after removal from the hygrothermal environment. This undermines the possible adverse effects on bond strength during testing due to hygrothermal environments. Recently, some researchers maintained a deteriorating environment during testing to overcome this shortcoming [90,163].

7. Conclusions

The following observations can be concluded from the above discussion-

- Mechanical interlocking and chemical bonding are primarily responsible for the FRP-Concrete bond.
- Chemical adhesion or bonding is more susceptible to moisture compared to mechanical interlocking. For this, the rougher surface, which has good mechanical interlocking, shows a better resistance against moisture.
- The glass transition temperature (Tg) of epoxy/adhesive plays a vital role in FRP-Concrete strength. This Tg is susceptible to temperature change and moisture present in the epoxy/adhesive.
- The FRP-Concrete bond deteriorates severely when the surrounding temperature exceeds the glass transition temperature (Tg) of epoxy/adhesive and the humidity is low.
- The mode of failure of FRP-Concrete bond shifts from the concrete substrate to adhesive due to its degradation for temperature and/or humidity.
- In moist conditions, dry layup performs better than traditional wet layup in terms of shear strength.
- In general, the performance of FRP laminate is found to be poorer than the equivalent FRP sheets for most hygrothermal cases. The susceptibility of adhesive to moisture, which is used in greater amounts in laminate, may be responsible for this.
- The accuracy of bond strength prediction of an analytical model of FRP-Concrete bond is found high when the model considers parameters related to the material properties change under environmental exposure.
- Among numerical models, the direct modeling approach of the FRP-Concrete bond is found to be the best predictive numerical approach, whereas the interface model approach is the most common due to its simplicity.
- Usually, bond slip behaviors that are developed considering hygrothermal effects are used for the numerical modeling of FRP-Concrete bond subjected to hygrothermal environment.
- Usually, the test samples of FRP-Concrete bond remain under hygrothermal environment during their exposure. But, the exposure is not maintained while testing the samples. This undermines the possible adverse effects on bond strength during testing due to hygrothermal environments.
- Few studies are available to quantify the contribution of mechanical interlocking and chemical bonding separately in FRP-Concrete bond under hygrothermal environment. Future research can be focused on quantifying the contribution separately in the specified condition.
- Most FRP-Concrete models consider substrate failure, whereas other modes or combinations of different failure modes are possible. Further effort can be carried out to develop models considering other possible failure modes to define the FRP-Concrete bond model more realistically.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

The authors would like to acknowledge the funding provided by National Natural Science Foundation of China (NSFC 52178097). The first author also would like to acknowledge the support of Dr. Faisal Mukhtar (King Fahd University of Petroleum & Minerals, Saudi Arabia).

References

[1] H.T. Ali, R. Akrami, S. Fotouhi, M. Bodaghi, M. Saeedifar, M. Yusuf, M. Fotouhi, Fiber reinforced polymer composites in bridge industry, Structures 30 (2021) 774–785, https://doi.org/10.1016/j.istruc.2020.12.092.
[2] M.H. Akeed, S. Qaidi, H.U. Ahmed, R.H. Faraj, A.S. Mohammed, W. Emad, B. A. Tayeh, A.R.G. Azevedo, Ultra-high-performance fiber-reinforced concrete. Part II: Hydration and microstructure, Case Stud Constr. Mater. 17 (2022) e01289.
[3] P. Colombi, G. Fava, C. Poggi, End debonding of CFRP wraps and strips for the strengthening of concrete structures, Compos. Struct. 111 (2014) 510–521, https://doi.org/10.1016/j.compstruct.2014.01.029.
[4] S.M. Raoof, L.N. Koutas, D.A. Bournas, Textile-reinforced mortar (TRM) versus fibre-reinforced polymers (FRP) in flexural strengthening of RC beams, Constr. Build. Mater. 151 (2017) 279–291, https://doi.org/10.1016/j.conbuildmat.2017.05.023.
[5] Y. Duo, X. Liu, Y. Liu, T. Tafsirojjaman, M. Sabbrojjaman, Environmental impact on the durability of FRP reinforcing bars, J. Build. Eng. 43 (2021), 102909, https://doi.org/10.1016/j.jobe.2021.102909.
[6] T. Tafsirojjaman, S. Fawzia, D.P. Thambiratnam, N. Wirth, Performance of FRP strengthened full-scale simply-supported circular hollow steel members under monotonic and large-displacement cyclic loading, Eng. Struct. 242 (2021), 112522, https://doi.org/10.1016/j.engstruct.2021.112522.
[7] Y. Liu, H. Zhang, T. Tafsirojjaman, A. Ur, R. Dogar, O. Alajarmeh, Q. Yue, A. Manalo, A novel technique to improve the compressive strength and ductility of glass fiber reinforced polymer (GFRP) composite bars, Constr. Build. Mater. 326 (2022), 126782, https://doi.org/10.1016/j.conbuildmat.2022.126782.

[8] T. Tafsirojjaman, S. Fawzia, D. Thambiratnam, X.L. Zhao, FRP strengthened SHS beam-column connection under monotonic and large-deformation cyclic loading, Thin-Walled Struct. 161 (2021), 107518, https://doi.org/10.1016/j.tws.2021.107518.
[9] Y. Liu, J.Z. Xie, T. Tafsirojjaman, Q.R. Yue, C. Tan, G.J. Che, CFRP lamella stay-cable and its force measurement based on microwave radar, Case Stud. Constr. Mater. 16 (2022) e00824.
[10] T. Tafsirojjaman, S. Fawzia, D.P. Thambiratnam, X.L. Zhao, Study on the cyclic bending behaviour of CFRP strengthened full-scale CHS members, Structures. 28 (2020) 741–756, https://doi.org/10.1016/j.istruc.2020.09.015.
[11] W. Li, P. Huang, Z. Chen, X. Zheng, Y. Yang, X. Guo, Bond behavior of fully bonded CFRP-concrete interface with improved double shear tests, J. Build. Eng. 43 (2021), 102866, https://doi.org/10.1016/j.jobe.2021.102866.
[12] J. Li, Z. Mai, J. Xie, Z. Lu, Durability of components of FRP-concrete bonded reinforcement systems exposed to chloride environments, Compos. Struct. 279 (2022), 114697, https://doi.org/10.1016/j.compstruct.2021.114697.
[13] R.A. Hawileh, N. Al Nuaimi, W. Nawaz, J.A. Abdalla, M.G. Sohail, Flexural and Bond Behavior of Concrete Beams Strengthened with CFRP and Galvanized Steel Mesh Laminates, Pract. Period. Struct. Des. Constr. 27 (2022), https://doi.org/10.1061/(ASCE)SC.1943-5576.0000651.
[14] Y. Liu, T. Tafsirojjaman, A.U.R. Dogar, A. Hückler, Bond behaviour improvement between infra-lightweight and high strength concretes using FRP grid reinforcements and development of bond strength prediction models, Constr. Build. Mater. 270 (2021), 121426, https://doi.org/10.1016/j.conbuildmat.2020.121426.
[15] T. Tafsirojjaman, S. Fawzia, D. Thambiratnam, X.L. Zhao, Seismic strengthening of rigid steel frame with CFRP, Arch. Civ. Mech. Eng. 19 (2019) 334–347, https://doi.org/10.1016/j.acme.2018.08.007.
[16] M. Molina, J.J. Cruz, S. Oller, A.H. Barbat, L. Gil, Ingeniería e investigación, accessed September 18, 2017, Ing. e Investig. 31 (2011) 26–39, http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0120-56092011000300004&lng=en&nrm=iso&tlng=en.
[17] B. Wan, M.F. Petrou, K.A. Harries, M.A. Sutton, B. Yang, Experimental Investigation of Bond Between FRP and Concrete, in: 3rd Int. Conf. Compos. Infrastructures ICCI'02, 2002. http://sem-proceedings.com/03s/sem.org-2003-SEM-Ann-Conf-s32p03-Experimental-Investigation-Bond-Between-FRP-Concrete.pdf.
[18] J.G. Teng, FRP-strengthened RC structures, Wiley, 2002.
[19] C. Caggegi, V. Pensée, M. Fagone, M. Cuomo, L. Chevalier, Experimental global analysis of the efficiency of carbon fiber anchors applied over CFRP strengthened bricks, Constr. Build. Mater. 53 (2014) 203–212, https://doi.org/10.1016/j.conbuildmat.2013.11.086.
[20] I. Iovinella, A. Prota, C. Mazzotti, Influence of surface roughness on the bond of FRP laminates to concrete, Constr. Build. Mater. 40 (2013) 533–542, https://doi.org/10.1016/j.conbuildmat.2012.09.112.
[21] J.C. López-González, J. Fernández-Gómez, E. González-Valle, Effect of Adhesive Thickness and Concrete Strength on FRP-Concrete Bonds, J. Compos. Constr. 16 (2012) 705–711, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000303.
[22] C. Carloni, K.V. Subramaniam, M. Savoia, C. Mazzotti, Experimental determination of FRP–concrete cohesive interface properties under fatigue loading, Compos. Struct. 94 (2012) 1288–1296, https://doi.org/10.1016/j.compstruct.2011.10.026.
[23] Y.J. Kim, P.J. Heffernan, Fatigue Behavior of Externally Strengthened Concrete Beams with Fiber-Reinforced Polymers: State of the Art, J. Compos. Constr. 12 (2008) 246–256, https://doi.org/10.1061/(ASCE)1090-0268(2008)12:3(246).
[24] J.G. Dai, Y. Saito, T. Ueda, Y. Sato, Static and Fatigue Bond Characteristics of Interfaces between CFRP Sheets and Frost Damage Experienced Concrete, in: Proc. Seventh Int. Symp. Fiber-Reinforced Polym. Reinf. Reinf. Concr. Struct., Kansas City, Missouri, 2005: pp. 1515–1530. https://www.researchgate.net/profile/Tamon_Ueda/publication/241258230_Static_and_Fatigue_Bond_Characteristics_of_Interfaces_between_CFRP_Sheets_and_Frost_Damage_Experienced_Concrete/links/56e811cb08ae9aecadbac18d.pdf (accessed September 18, 2017).
[25] P. Dohnálek, Environmental durability of FRP bond to concrete subjected to freeze-thaw action, Massachusetts Institute of Technology, 2006 accessed September 18, 2017.
[26] J. Shrestha, T. Ueda, D. Zhang, Durability of FRP Concrete Bonds and Its Constituent Properties under the Influence of Moisture Conditions, J. Mater. Civ. Eng. 27 (2015) A4014009, https://doi.org/10.1061/(ASCE)MT.1943-5533.0001093.
[27] J. Tatar, S. Milev, Durability of Externally Bonded Fiber-Reinforced Polymer Composites in Concrete Structures: A Critical Review, Polymers (Basel) 13 (2021) 765, https://doi.org/10.3390/polym13050765.
[28] Y.L. Wang, X.Y. Guo, S.Y.H. Shu, Y.C. Guo, X.M. Qin, Effect of salt solution wet-dry cycling on the bond behavior of FRP-concrete interface, Constr. Build. Mater. 254 (2020), 119317, https://doi.org/10.1016/j.conbuildmat.2020.119317.
[29] J.-H. Xie, M.-W. Wei, P.-Y. Huang, H. Zhang, P.-S. Chen, Fatigue behavior of the basalt fiber-reinforced polymer/concrete interface under wet-dry cycling in a marine environment, Constr. Build. Mater. 228 (2019), 117065, https://doi.org/10.1016/j.conbuildmat.2019.117065.
[30] A. Ahmed, M. Zillur Rahman, Y. Ou, S. Liu, B. Mobasher, S. Guo, D. Zhu, A review on the tensile behavior of fiber-reinforced polymer composites under varying strain rates and temperatures, Constr. Build. Mater. 294 (2021), 123565, https://doi.org/10.1016/j.conbuildmat.2021.123565.
[31] B. Shadravan, F.M. Tehrani, A Review of Direct Shear Testing Configurations for Bond between Fiber-Reinforced Polymer Sheets on Concrete and Masonry Substrates, Period. Polytech. Civ. Eng. (2017) 1–31, https://doi.org/10.3311/PPci.9090.
[32] L.L. Zhang, L. Zhang, J.X. Ma, Durability of the Bonding Performance of Frp-Concrete Interface Externally Bonded With FRP Composite Sheet, in: S.T. Smith (Ed.), Asia-Pacific Conf. FRP Struct. (APFIS 2007), International Institute for FRP in Construction, Hong Kong, 2007: pp. 901–906.
[33] M.I. Kabir, R. Shrestha, B. Samali, Effects of applied environmental conditions on the pull-out strengths of CFRP-concrete bond, Constr. Build. Mater. 114 (2016) 817–830, https://doi.org/10.1016/j.conbuildmat.2016.03.195.
[34] Z. Ouyang, B. Wan, Nonlinear Deterioration Model for Bond Interfacial Fracture Energy of FRP-Concrete Joints in Moist Environments, J. Compos. Constr. 13 (2009) 53–63, https://doi.org/10.1061/(ASCE)1090-0268(2009)13:1(53).
[35] M.A. Abanilla, V.M. Karbhari, Y. Li, Interlaminar and intralaminar durability characterization of wet layup carbon/epoxy used in external strengthening, Compos. Part B Eng. 37 (2006) 650–661, https://doi.org/10.1016/j.compositesb.2006.02.023.
[36] Y. Yun, Y.-F. Wu, Durability of CFRP–concrete joints under freeze–thaw cycling, Cold Reg. Sci. Technol. 65 (2011) 401–412, https://doi.org/10.1016/j.coldregions.2010.11.008.
[37] Y. Wang, G. Cai, A. Si Larbi, D. Waldmann, K. Daniel Tsavdaridis, J. Ran, Monotonic axial compressive behaviour and confinement mechanism of square CFRP-steel tube confined concrete, Eng. Struct. 217 (2020), 110802, https://doi.org/10.1016/j.engstruct.2020.110802.
[38] P. Kumar, A. Kumar, S. Erlicher, A modified hybrid Van der Pol–Duffing–Rayleigh oscillator for modelling the lateral walking force on a rigid floor, Phys. D Nonlinear Phenom. 358 (2017) 1–14, https://doi.org/10.1016/j.physd.2017.07.008.
[39] M.A.G. Silva, H.C. Biscaia, R. Marreiros, Bond–slip on CFRP/GFRP-to-concrete joints subjected to moisture, salt fog and temperature cycles, Compos. Part B Eng. 55 (2013) 374–385, https://doi.org/10.1016/j.compositesb.2013.06.015.
[40] M.A.G. Silva, H. Biscaia, Degradation of bond between FRP and RC beams, Compos. Struct. 85 (2008) 164–174, https://doi.org/10.1016/j.compstruct.2007.10.014.
[41] C. Mikami, H.-C.-C. Wu, A. Elarbi, Effect of hot temperature on pull-off strength of FRP bonded concrete, Constr. Build. Mater. 91 (2015) 180–186, https://doi.org/10.1016/j.conbuildmat.2015.05.013.
[42] R. Sen, Developments in the durability of FRP-concrete bond, Constr. Build. Mater. 78 (2015) 112–125, https://doi.org/10.1016/j.conbuildmat.2014.12.106.
[43] M. Heshmati, R. Haghani, M. Al-Emrani, Environmental durability of adhesively bonded FRP/steel joints in civil engineering applications: State of the art, Compos. Part B Eng. 81 (2015) 259–275, https://doi.org/10.1016/j.compositesb.2015.07.014.
[44] J. Wang, H. GangaRao, R. Liang, W. Liu, Durability and prediction models of fiber-reinforced polymer composites under various environmental conditions: A critical review, J. Reinf. Plast. Compos. 35 (2016) 179–211, https://doi.org/10.1177/0731684415610920.
[45] E.H. Immergut, H.F. Mark, Plasticization and Plasticizer Processes, American Chemical Society, Washington, D.C., 1965. https://doi.org/10.1021/ba-1965-0048.ch001.
[46] B.P. Blackburn, J. Tatar, E.P. Douglas, H.R.R. Hamilton, Effects of hygrothermal conditioning on epoxy adhesives used in FRP composites, Constr. Build. Mater. 96 (2015) 679–689, https://doi.org/10.1016/j.conbuildmat.2015.08.056.
[47] M. Frigione, M.A. Aiello, C. Naddeo, Water effects on the bond strength of concrete/concrete adhesive joints, Constr. Build. Mater. 20 (2006) 957–970, https://doi.org/10.1016/j.conbuildmat.2005.06.015.
[48] S. Choi, Study of hygrothermal effects and cure kinetics on the structure-property relations of epoxy-amine thermossets: fundamental analysis and application, University of Florida, 2011.
[49] S.E. Buck, D.W. Lischer, S. Nemat-Nasser, The Durability of E-Glass/Vinyl Ester Composite Materials Subjected to Environmental Conditioning and Sustained Loading, J. Compos. Mater. 32 (1998) 874–892, https://doi.org/10.1177/002199839803200904.
[50] E. Ferrier, P. Hamelin, Effect of water absorption on the durability of carbon FRP reinforcement, in: 2nd Int. Conf. Durab. Fibre Reinf. Polym. Compos. Constr., Montréal, 2002: pp. 99–112.
[51] E. Douglas, Introduction to Materials Science and Engineering: A Guided Inquiry, Pearson Higher Education Inc, Upper Sadle River, New Jersey, 2013.
[52] E.-L. Klamer, D.A. Hordijk, C.S. Kleinman, Debonding of CFRP laminates externally bonded to concrete specimens at low and high temperatures, in: Proc. Third Int. Conf. Compos. Civ. Eng. (CICE 2006),Mirmiran A Nanni A, Miami, Florida, 2006: pp. 35–38. http://www.ernstklamer.nl/pdf/paper Miami.pdf.
[53] A. Stewart, Study Of Cement – Epoxy Interfaces , Accelerated Testing , And Surface Modification Ation, University of Florida, 2012. https://search.proquest.com/docview/1368996623?accountid=27795.
[54] J. Zhou, J.P. Lucas, Hygrothermal effects of epoxy resin. Part II: variations of glass transition temperature, Polymer (Guildf) 40 (1999) 5513–5522, https://doi.org/10.1016/S0032-3861(98)00791-5.
[55] Y. Yang, G. Xian, H. Li, L. Sui, Thermal aging of an anhydride-cured epoxy resin, Polym. Degrad. Stab. 118 (2015) 111–119, https://doi.org/10.1016/j.polymdegradstab.2015.04.017.
[56] A.P. Chakraverty, U.K. Mohanty, S.C. Mishra, B.B. Biswal, Effect of Hydrothermal immersion and Hygrothermal Conditioning on Mechanical Properties of GRE Composite, IOP Conf. Ser. Mater. Sci. Eng. 178 (2017), 012013, https://doi.org/10.1088/1757-899X/178/1/012013.

[57] Y. Bin Park, J.H. Kweon, J.H. Choi, Failure characteristics of carbon/BMI-Nomex sandwich joints in various hygrothermal conditions, Compos. Part B Eng. 60 (2014) 213–221, https://doi.org/10.1016/j.compositesb.2013.12.035.
[58] N. Guermazi, A. Ben Tarjem, I. Ksouri, H.F. Ayedi, On the durability of FRP composites for aircraft structures in hygrothermal conditioning, Compos. Part B Eng. 85 (2013) 294–304, https://doi.org/10.1016/j.compositesb.2015.09.035.
[59] G. Alawsi, S. Aldajah, S.A. Rahmaan, Impact of humidity on the durability of E-glass/polymer composites, Mater. Des. 30 (2009) 2506–2512, https://doi.org/10.1016/j.matdes.2008.10.002.
[60] M. Wang, X. Xu, J. Ji, Y. Yang, J. Shen, M. Ye, The hygrothermal aging process and mechanism of the novolac epoxy resin, Compos. Part B Eng. 107 (2016) 1–8, https://doi.org/10.1016/j.compositesb.2016.09.067.
[61] B.P. Blackburn, Effects of hygrothermal conditioning on epoxy adhesives used in FRP composites, University of Florida, 2013.
[62] K. Al-Lami, P. Colombi, T. D`Antino, Influence of hygrothermal ageing on the mechanical properties of CFRP-concrete joints and of their components, Compos. Struct. 238 (2020), 111947, https://doi.org/10.1016/j.compstruct.2020.111947.
[63] P. Kumar, A. Patnaik, S. Chaudhary, A review on application of structural adhesives in concrete and steel–concrete composite and factors influencing the performance of composite connections, Int. J. Adhes. Adhes. 77 (2017) 1–14, https://doi.org/10.1016/j.ijadhadh.2017.03.009.
[64] J. He, J. Shi, Z. Lu, Assessment of interfacial fracture energy between concrete and CFRP under water immersion conditions, Constr. Build. Mater. 285 (2021), 122942, https://doi.org/10.1016/j.conbuildmat.2021.122942.
[65] J.F. Chen, Y. Tao, Finite Element Modelling of FRP-to-Concrete Bond Behaviour Using the Concrete Damage Plasticity Theory Combined with a Plastic Degradation Model, in: CICE 2010 - 5th Int. Conf. FRP Compos. Civ. Eng., Beijing, China, 2010: pp. 45–50. https://link.springer.com/content/pdf/10.1007/978-3-642-17487-2_7.pdf (accessed September 16, 2017).
[66] Y. Tao, J.F. Chen, Concrete Damage Plasticity Model for Modeling FRP-to-Concrete Bond Behavior, J. Compos. Constr. 19 (2015) 04014026, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000482.
[67] J.F. Chen, J.G. Teng, Anchorage Strength Models for FRP and Steel Plates Bonded to Concrete, J. Struct. Eng. 127 (2001) 784–791, https://doi.org/10.1061/(ASCE)0733-9445(2001)127:7(784).
[68] M.R. Garcez, A.B. Rohden, L.C. Meneghetti, R. Gravina, Influence of concrete compressive strength on the debonding failure of externally bonded carbon fiber reinforced polymers, J. Build. Pathol. Rehabil. 6 (2021) 20, https://doi.org/10.1007/s41024-021-00116-3.
[69] Z.P. Bazant, P.C. Prat, Effect of temperature and humidity on fracture energy of concrete, ACI Mater. J. 85 (1988) 262–271. http://www.civil.northwestern.edu/people/bazant/PDFs/Papers - Backup 2_20_2013/233.pdf (accessed September 16, 2017).
[70] H. Kallel, H. Carré, C. La Borderie, B. Masson, N.C. Tran, Effect of temperature and moisture on the instantaneous behaviour of concrete, Cem. Concr. Compos. 80 (2017) 326–332, https://doi.org/10.1016/j.cemconcomp.2017.03.021.
[71] A.J.B. Tadeu, F.J.F.G. Branco, Shear Tests of Steel Plates Epoxy-Bonded to Concrete under Temperature, J. Mater. Civ. Eng. 12 (2000) 74–80, https://doi.org/10.1061/(ASCE)0899-1561(2000)12:1(74).
[72] A.M. Neville, Durability of Concrete, in: Prop. Concr. , 5th Editio, Pearson Education Limited, Harlow, 2011: pp. 483–531. https://igitgeotech.files.wordpress.com/2014/10/properties-of-concrete-by-a-m-neville.pdf (accessed September 16, 2017).
[73] F.M. Mukhtar, R.M. Faysal, A review of test methods for studying the FRP-concrete interfacial bond behavior, Constr. Build. Mater. 169 (2018) 877–887, https://doi.org/10.1016/j.conbuildmat.2018.02.163.
[74] H.C. Biscaia, C. Chastre, A. Viegas, N. Franco, Numerical modelling of the effects of elevated service temperatures on the debonding process of FRP-to-concrete bonded joints, Compos. Part B Eng. 70 (2015) 64–79, https://doi.org/10.1016/j.compositesb.2014.10.041.
[75] E. Ferrier, A. Agbossou, Temperature effects on the shear capacity of external bonded fiber reinforced polymer on concrete, Constr. Build. Mater. 152 (2017) 333–344, https://doi.org/10.1016/j.conbuildmat.2017.07.002.
[76] Y. Li, X. Liu, M. Wu, Mechanical properties of FRP-strengthened concrete at elevated temperature, Constr. Build. Mater. 134 (2017) 424–432, https://doi.org/10.1016/j.conbuildmat.2016.12.148.
[77] A.S. Crasto, R.Y. Kim, Environmental Durability of A Composite-to- Composite Adhesive Bond in Infrastructure Applications, in, Technol. Transf. a Glob. Community (1996) 837–849.
[78] E. Ferrier, O. Rabinovitch, L. Michel, Mechanical behavior of concrete–resin/adhesive–FRP structural assemblies under low and high temperatures, Constr. Build. Mater. 127 (2016) 1017–1028, https://doi.org/10.1016/j.conbuildmat.2015.12.127.
[79] D. Lau, Moisture-induced Debonding in Concrete-epoxy Interface, HKIE Trans. Hong Kong Inst. Eng. 19 (2012) 33–38, https://doi.org/10.1080/1023697X.2012.10668995.
[80] P. Böer, L. Holliday, T.-H.-K.-H.-K. Kang, Independent environmental effects on durability of fiber-reinforced polymer wraps in civil applications: A review, Constr. Build. Mater. 48 (2013) 360–370, https://doi.org/10.1016/j.conbuildmat.2013.06.077.
[81] B. Ghiassi, G. Marcari, D.V. Oliveira, P.B. Lourenço, Water degrading effects on the bond behavior in FRP-strengthened masonry, Compos. Part B Eng. 54 (2013) 11–19, https://doi.org/10.1016/j.compositesb.2013.04.074.
[82] V.M. Karbhari, M. Engineer, D.A. Eckel, On the durability of composite rehabilitation schemes for concrete: use of a peel test, accessed October 2, 2017, J. Mater. Sci. 32 (1997) 147–156, https://link.springer.com/content/pdf/10.1023%2FA%3A1018591619404.pdf.
[83] M.A. Aiello, M. Frigione, D. Acierno, Effects of environmental conditions on performance of polymeric adhesives for restoration of concrete structures, J. Mater. Civ. Eng. 14 (2002) 185–189, https://doi.org/10.1061/(ASCE)0899-1561(2002)14:2(185).
[84] B. Wan, M.F. Petrou, K.A. Harries, The effect of the presence of water on the durability of bond between CFRP and concrete, J. Reinf. Plast. Compos. 25 (2006) 875–890, https://doi.org/10.1177/0731684406065140.
[85] C. Au, O. Büyüköztürk, Peel and Shear Fracture Characterization of Debonding in FRP Plated Concrete Affected by Moisture, J. Compos. Constr. 10 (2006) 35–47, https://doi.org/10.1061/(ASCE)1090-0268(2006)10:1(35).
[86] A. Zhou, O. Büyüköztürk, D. Lau, Debonding of concrete-epoxy interface under the coupled effect of moisture and sustained load, Cem. Concr. Compos. 80 (2017) 287–297, https://doi.org/10.1016/j.cemconcomp.2017.03.019.
[87] V.M. Karbhari, L. Zhao, Issues related to composite plating and environmental exposure effects on composite-concrete interface in external strengthening, Compos. Struct. 40 (1997) 293–304, https://doi.org/10.1016/S0263-8223(98)00031-2.
[88] H. a. Toutanji, W. Gómez,, Durability characteristics of concrete beams externally bonded with FRP composite sheets, Cem. Concr. Compos. 19 (1997) 351–358, https://doi.org/10.1016/S0958-9465(97)00028-0.
[89] J. Dai, H. Yokota, M. Iwanami, E. Kato, Experimental Investigation of the Influence of Moisture on the Bond Behavior of FRP to Concrete Interfaces, J. Compos. Constr. 14 (2010) 834–844, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000142.
[90] J. Shrestha, D. Zhang, T. Ueda, Bond-slip models for FPR-concrete interfaces subjected to moisture conditions, Int. J. Polym. Sci. 2017 (2017) 1–14, https://doi.org/10.1155/2017/4031565.
[91] U. Tamon, J. Shrestha, Z. Dawei, Moisture Effects on FRP-Concrete Interface Property, in: APFIS2017 - 6th Asia-Pacific Conf. FRP Struct., Singapore, 2017: pp. 19–21.
[92] T. Ueda, J. Shrestha, K. Rashid, Moisture and Temperature Effects on Interface Mechanical Properties for External Bonding, in: Proc. 5th Int. Conf. Durab. Concr. Struct., Purdue University Press, 2016: pp. 3–12. https://doi.org/10.5703/1288284316105.
[93] U. Tamon, J. Shrestha, K. Rashid, Y. Qian, Z. Dawei, Long-Term Performance of External Bonding Under Moisture and Temperature Effects, in: D.A. Hordijk, M. Luković (Eds.), High Tech Concr. Where Technol. Eng. Meet, Springer International Publishing, Cham, 2018, pp. 1867–1876, https://doi.org/10.1007/978-3-319-59471-2_214.
[94] M.S. Sciolti, M.A. Aiello, M. Frigione, Influence of water on bond behavior between CFRP sheet and natural calcareous stones, Compos. Part B Eng. 43 (2012) 3239–3250, https://doi.org/10.1016/j.compositesb.2012.03.002.
[95] Y. Pan, G. Xian, M.A.G. Silva, Effects of water immersion on the bond behavior between CFRP plates and concrete substrate, Constr. Build. Mater. 101 (2015) 326–337, https://doi.org/10.1016/j.conbuildmat.2015.10.129.
[96] V.M. Karbhari, R. Navada, Investigation of durability and surface preparation associated defect criticality of composites bonded to concrete, Compos. Part A Appl. Sci. Manuf. 39 (2008) 997–1006, https://doi.org/10.1016/j.compositesa.2008.03.003.
[97] J.J. Myers, M. Ekenel, Effect of Environmental Conditions on Bond Strength between CFRP Laminate and Concrete Substrate, in: Proc., FRPRCS-7, American Concrete Institute, Kansas , 2005: pp. 1571-1592. http://www.quakewrap.com/frp papers/EffectofEnvironmentalConditionsonBond StrengthbetweenCFRPLaminateandConcreteSubstrate.pdf (accessed September 27, 2017).
[98] N.V. Datla, M. Papini, J. Ulicny, B. Carlson, J.K. Spelt, The effects of test temperature and humidity on the mixed-mode fatigue behavior of a toughened adhesive aluminum joint, Eng. Fract. Mech. 78 (2011) 1125–1139, https://doi.org/10.1016/j.engfracmech.2011.01.028.
[99] X.H. Zheng, P.Y. Huang, G.M. Chen, X.M. Tan, Fatigue behavior of FRP–concrete bond under hygrothermal environment, Constr. Build. Mater. 95 (2015) 898–909, https://doi.org/10.1016/j.conbuildmat.2015.07.172.
[100] G. Qin, P. Huang, H. Zhou, X. Guo, X. Zheng, Fatigue and durability behavior of RC beams strengthened with CFRP under hot-wet environment, Constr. Build. Mater. 111 (2016) 735–742, https://doi.org/10.1016/j.conbuildmat.2016.02.131.
[101] M.I. Kabir, B. Samali, R. Shrestha, Experimental Study On Durability Of CFRP-Concrete Bond Subjected To Temperature, Humidity And Outdoor Environment, in: Fourth Asia-Pacific Conf. FRP Struct. (APFIS 2013), International Institute for FRP in Construction, Melbourne, 2013.
[102] D. Lau, O. Büyüköztürk, Fracture characterization of concrete/epoxy interface affected by moisture, Mech. Mater. 42 (2010) 1031–1042, https://doi.org/10.1016/j.mechmat.2010.09.001.
[103] J. Lyons, D. Laub, V. Giurgiutiu, M. Petrou, H. Salem, Effect of Hygrothermal Aging on the Fracture of Composite Overlays on Concrete, J. Reinf. Plast. Compos. 21 (2002) 293–309, https://doi.org/10.1177/0731684402021004256.
[104] Craftech Industries, The Pultrusion Process: Manufacturing Fiber Reinforced Polymers, (n.d.). http://www.craftechind.com/the-pultrusion-process-manufacturing-fiber-reinforced-polymers/ (accessed September 20, 2017).
[105] G. Erhard, Designing with plastics, Hanser, 2006. https://books.google.com.sa/books?id=mesU4WbE5CIC&printsec=frontcover&dq=Designing+with+Plastics&redir_esc=y (accessed February 18, 2018).
[106] N.F.N.F. Grace, S.B.S.B.B. Singh, Durability evaluation of carbon fiber-reinforced polymer strengthened concrete beams: Experimental study and design, ACI

Struct. J. 102 (2005) 40–53. https://www.scopus.com/record/display.uri?eid=2-s2.0-14244256102&origin=inward&txGid=d858c5e60994fbe6680899a561f01518 (accessed September 19, 2017).
[107] C.W. Dolan, J. Tanner, D. Mukai, H.R. Hamilton, E. Douglas, Research report for evaluating the durability of bonded CFRP repair/strengthening of concrete beams, 2009.
[108] V.M. Karbhari, K. Ghosh, Comparative durability evaluation of ambient temperature cured externally bonded CFRP and GFRP composite systems for repair of bridges, Compos. Part A Appl. Sci. Manuf. 40 (2009) 1353–1363, https://doi.org/10.1016/j.compositesa.2009.01.011.
[109] J.R.R. Cromwell, K.A.A. Harries, B.M.M. Shahrooz, Environmental durability of externally bonded FRP materials intended for repair of concrete structures, Constr. Build. Mater. 25 (2011) 2528–2539, https://doi.org/10.1016/j.conbuildmat.2010.11.096.
[110] Z.S. Hiroyuki, Y. Wu, Analysis of debonding fracture properties of CFS strengthened member subject to tension, in: Proc. 3rd Int. Symp. Non-Metallic Reinf. Concr. Struct., Japan Concrete Institute, Sapporo, Japan, 1997: pp. 287–294.
[111] T. Tanaka, Shear resisting mechanism of reinforced concrete beams with CFS as shear reinforcement, Hokkaido University, Japan., 1996.
[112] T. Maeda, Y. Asano, Y. Sato, T. Ueda, Y. Kakuta, A study on bond mechanism of carbon fiber sheet, in: Proc. 3rd Int. Symp. Non-Metallic Reinf. Concr. Struct., Japan Concrete Institute: Tokyo, Japan, Sapporo, Japan, 1997: pp. 279–286.
[113] P. Holzenkämpfer, Ingenieurmodelle des verbundes geklebter bewehrung für betonbauteile, TU Braunschweig, 1994. Ph.D Thesis.
[114] B. Täljsten, Plate bonding: Strengthening of existing concrete structures with epoxy bonded plates of steel or fibre reinforced plastics, (Doctoral dissertation, Luleå tekniska universitet)., 1994.
[115] H. Yuan, Z. Wu, Interfacial fracture theory in structures strengthened with composite of continuous fiber, in: Proc., Symp. China Japan Sci. Technol. 21st Century, Tokyo, 1999: pp. 142–155.
[116] M. Blaschko, R. Niedermeier, K. Zilch, Bond failure modes of flexural members strengthened with FRP, in: H. Saadatmanesh, M.R. Ehsani (Eds.), Fiber Compos. Infrastruct., Proc., 2nd Int. Conf. Compos. Infrastruct., 1996: pp. 315–327.
[117] U. Neubauer, F. Rostasy, Design aspects of concrete struc-tures strengthened with externally bonded CFRP plates., in: Proc. 7th Int. Conf. Struct. Faults Repair, ECS Publications, Edinburgh (Scotland), 1997: pp. 107–118.
[118] Z. Wu, H. Yuan, H. Yoshizawa, T. Kanakubo, Exprimental/Analytical Study on Interfacial Fracture Energy and Fracture Propagation Along FRPConcrete Interface, in: Spec. Ed. Mech. Concr. Mater., 2001: pp. 201,133–152.
[119] D. Van Gemert, Force transfer in epoxy bonded steel/concrete joints, Int. J. Adhes. Adhes. 1 (1980) 67–72, https://doi.org/10.1016/0143-7496(80)90060-3.
[120] A. Singh, E. del Rey Castillo, J. Ingham, FRP-to-FRP bond characterization and force-based bond length model, Compos. Struct. 210 (2019) 724–734, https://doi.org/10.1016/j.compstruct.2018.12.005.
[121] S. Matthys, M. Blaschko, H. Blontrock, E. David, M. Leeming, Special design considerations and environmental effects, in: 2001: pp. 109–118. https://doi.org/10.35789/fib.BULL.0014.Ch09.
[122] Z. Wu, S.M. Islam, H. Said, A Three-Parameter Bond Strength Model for FRP—Concrete Interface, J. Reinf. Plast. Compos. 28 (2009) 2309–2323. https://doi.org/10.1177/0731684408091961.
[123] TR 55, Design Guidance for Strengthening Concrete Structures Using Fibre Composite Materials, 3rd ed., Concrete Society: Camberley, UK, 2012.
[124] Y.X. Yang, Q.R. Yue, Y.C. Hu, Experimental study on bond performance between carbon fiber sheets and concrete, J. Build. Struct. 22 (2001) 36–42.
[125] Japan Concrete Institute (JCI), Technical report of technical committee on retrofit technology, in: Proc. Int. Symp. Latest Achiev. Technol. Res. Retrofit. Concr. Struct., Japan Concrete Institute (JCI), Kyoto, Japan, 2003.
[126] SIA 166, Kelebebewehrungen (Externally Bonded Reinforcement), Schweizerichenr Ingegneur-und Architektenveirein SIA: Zurich, Switzerland, 2004.
[127] J. Dai, T. Ueda, Y. Sato, Development of the Nonlinear Bond Stress-Slip Model of Fiber Reinforced Plastics Sheet-Concrete Interfaces with a Simple Method, J. Compos. Constr. 9 (2005) 52–62, https://doi.org/10.1061/(ASCE)1090-0268(2005)9:1(52).
[128] Y. Wu, Z. Zhou, Q. Yang, W. Chen, On shear bond strength of FRP-concrete structures, Eng. Struct. 32 (2010) 897–905, https://doi.org/10.1016/j.engstruct.2009.12.017.
[129] X.Z. Lu, J.G. Teng, L.P. Ye, J.J. Jiang, Bond–slip models for FRP sheets/plates bonded to concrete, Eng. Struct. 27 (2005) 920–937, https://doi.org/10.1016/j.engstruct.2005.01.014.
[130] J.P. Barrett, The Coefficient of Determination—Some Limitations, Am. Stat. 28 (1974) 19–20, https://doi.org/10.1080/00031305.1974.10479056.
[131] A. Cascardi, F. Micelli, ANN-Based Model for the Prediction of the Bond Strength between FRP and Concrete, Fibers. 9 (2021) 46, https://doi.org/10.3390/fib9070046.
[132] Y.T. Obaidat, S. Heyden, O. Dahlblom, The effect of CFRP and CFRP/concrete interface models when modelling retrofitted RC beams with FEM, Compos. Struct. 92 (2010) 1391–1398, https://doi.org/10.1016/j.compstruct.2009.11.008.
[133] G.M. Chen, J.F. Chen, J.G. Teng, On the finite element modelling of RC beams shear-strengthened with FRP, Constr. Build. Mater. 32 (2012) 13–26, https://doi.org/10.1016/j.conbuildmat.2010.11.101.
[134] C. a. Coronado, M.M. Lopez, Damage Approach for the Prediction of Debonding Failure on Concrete Elements Strengthened with FRP, J. Compos. Constr. 11 (2007) 391–400. https://doi.org/10.1061/(ASCE)1090-0268(2007)11:4(391).
[135] C.A. Coronado, M.M. Lopez, Experimental Characterization of Concrete-Epoxy Interfaces, J. Mater. Civ. Eng. 20 (2008) 303–312, https://doi.org/10.1061/(ASCE)0899-1561(2008)20:4(303).
[136] G. Camata, E. Spacone, R. Al-Mahaidi, V. Saouma, Analysis of Test Specimens for Cohesive Near-Bond Failure of Fiber-Reinforced Polymer-Plated Concrete, J. Compos. Constr. 8 (2004) 528–538, https://doi.org/10.1061/(ASCE)1090-0268(2004)8:6(528).
[137] H.B. Pham, R. Al-Mahaidi, V. Saouma, Modelling of CFRP–concrete bond using smeared and discrete cracks, Compos. Struct. 75 (2006) 145–150, https://doi.org/10.1016/j.compstruct.2006.04.039.
[138] F. An, Modelling of FRP-concrete interfacial bond behaviour, University Of Edinburgh, 2015.
[139] G.M. Chen, J.G. Teng, J.F. Chen, Finite-Element Modeling of Intermediate Crack Debonding in FRP-Plated RC Beams, J. Compos. Constr. 15 (2011) 339–353, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000157.
[140] Y. Yanchun, Durability Of Frp-Concrete Interface, City University Of Hong Kong, 2011. http://lbms03.cityu.edu.hk/theses/abt/phd-bc-b4086411xa.pdf (accessed November 20, 2017).
[141] J.-G. Dai, W.Y. Gao, J.G. Teng, Bond-Slip Model for FRP Laminates Externally Bonded to Concrete at Elevated Temperature, J. Compos. Constr. 17 (2013) 217–228, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000337.
[142] M.R.T. Arruda, J.P. Firmo, J.R. Correia, C. Tiago, Numerical modelling of the bond between concrete and CFRP laminates at elevated temperatures, Eng. Struct. 110 (2016) 233–243, https://doi.org/10.1016/j.engstruct.2015.11.036.
[143] C. Tuakta, O. Büyüköztürk, Deterioration of FRP/concrete bond system under variable moisture conditions quantified by fracture mechanics, Compos. Part B Eng. 42 (2011) 145–154, https://doi.org/10.1016/j.compositesb.2010.11.002.
[144] Z. Ouyang, B. Wan, An Analytical Model of FRP-Concrete Bond Deterioration in Moist Environment, Adv. Struct. Eng. 12 (2009) 761–769, https://doi.org/10.1260/136943309790327680.
[145] M. Khoshbakht, M.W. Lin, C.A. Feickert, A finite element model for hygrothermal analysis of masonry walls with FRP reinforcement, Finite Elem. Anal. Des. 45 (2009) 511–518, https://doi.org/10.1016/j.finel.2009.02.007.
[146] J.R. Philip, D.A. De Vries, Moisture movement in porous materials under temperature gradients, Trans. Am. Geophys. Union. 38 (1957) 222, https://doi.org/10.1029/TR038i002p00222.
[147] M. Heshmati, Hygrothermal Durability of Adhesively Bonded FRP/steel Joints, Chalmers University Of Technology, 2015.
[148] G. Mays, A.R. Hutchinson, Adhesive classification and properties, in: Adhes. Civ. Eng., Cambridge University Press, New York, 1992: pp. 30–75. https://books.google.com.sa/books?hl=en&lr=&id=KY6KYyo2Lo8C&oi=fnd&pg=PR3&dq=Adhesives+in+Civil+Engineering&ots=8X1L-w6fZs&sig=E3FIocanwjZhrhJgrL1KhgS758U&redir_esc=y#v=onepage&q=Adhesives in Civil Engineering&f=false (accessed October 2, 2017).
[149] H.A. Toutanji, Durability characteristics of concrete columns confined with advanced composite materials, Compos. Struct. 44 (1999) 155–161, https://doi.org/10.1016/S0263-8223(98)00125-1.
[150] M.A. Abanilla, Y. Li, V.M. Karbhari, Durability characterization of wet layup graphite/epoxy composites used in external strengthening (2005), https://doi.org/10.1016/j.compositesb.2005.05.016.
[151] D.R. Lefebvre, K.M. Takahashi, A.J. Muller, V.R. Raju, Degradation of epoxy coatings in humid environments: the critical relative humidity for adhesion loss, J. Adhes. Sci. Technol. 5 (1991) 201–227, https://doi.org/10.1163/156856191X00152.
[152] B. Ghiassi, P.B. Lourenço, D.V. Oliveira, Accelerated Hygrothermal Aging of Bond in FRP–Masonry Systems, J. Compos. Constr. 19 (2015) 04014051, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000506.
[153] V.M. Karbhari, M. Engineer, Investigation of Bond between Concrete and Composites: Use of a Peel Test, J. Reinf. Plast. Compos. 15 (1996) 208–227, https://doi.org/10.1177/073168449601500206.
[154] B. Yalim, A.S. Kalayci, A. Mirmiran, Performance of FRP-Strengthened RC Beams with Different Concrete Surface Profiles, J. Compos. Constr. 12 (2008) 626–634, https://doi.org/10.1061/(ASCE)1090-0268(2008)12:6(626).
[155] G.M. Chen, J.G. Teng, J.F. Chen, Process of debonding in RC beams shear-strengthened with FRP U-strips or side strips, Int. J. Solids Struct. 49 (2012) 1266–1282, https://doi.org/10.1016/j.ijsolstr.2012.02.007.
[156] A. Ali, J. Abdalla, R. Hawileh, K. Galal, CFRP Mechanical Anchorage for Externally Strengthened RC Beams under Flexure, Phys. Procedia. 55 (2014) 10–16, https://doi.org/10.1016/j.phpro.2014.07.002.
[157] R. Kalfat, R. Al-Mahaidi, Improvement of FRP-to-concrete bond performance using bidirectional fiber patch anchors combined with FRP spike anchors, Compos. Struct. 155 (2016) 89–98, https://doi.org/10.1016/j.compstruct.2016.08.010.
[158] S.V. Grelle, L.H. Sneed, Review of Anchorage Systems for Externally Bonded FRP Laminates, Int. J. Concr. Struct. Mater. 7 (2013) 17–33, https://doi.org/10.1007/s40069-013-0029-0.
[159] H. Zhou, D. Fernando, V. Thuan Nguyen, J.-G. Dai, The bond behaviour of CFRP-to-concrete bonded joints under fatigue cyclic loading: An experimental study,

Constr. Build. Mater. 273 (2021), 121674, https://doi.org/10.1016/j.conbuildmat.2020.121674.

[160] E. Cui, S. Jiang, J. Wang, X. Zeng, Bond behavior of CFRP-concrete bonding interface considering degradation of epoxy primer under wet-dry cycles, Constr. Build. Mater. 292 (2021), 123286, https://doi.org/10.1016/j.conbuildmat.2021.123286.

[161] M.A. Aiello, M. Leone, Interface analysis between FRP EBR system and concrete, Compos. Part B Eng. 39 (2008) 618–626, https://doi.org/10.1016/j.compositesb.2007.07.002.

[162] A. Momayez, M.R. Ehsani, A.A. Ramezanianpour, H. Rajaie, Comparison of methods for evaluating bond strength between concrete substrate and repair materials, Cem. Concr. Res. 35 (2005) 748–757, https://doi.org/10.1016/j.cemconres.2004.05.027.

[163] S.M. Raoof, D.A. Bournas, Bond between TRM versus FRP composites and concrete at high temperatures, Compos. Part B Eng. 127 (2017) 150–165, https://doi.org/10.1016/j.compositesb.2017.05.064.