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REVIEW ARTICLE

Bond behavior of CFRP-strengthened steel structures and its environmental influence factors: a critical review

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Abstract: Adhesively bonded carbon fiber-reinforced polymer (CFRP) systems have shown great promise for strengthening damaged steel structures, offering potential enhancements in the longevity of steel structures. However, the degradation of bond performance of CFRP under harsh environments remains a critical concern for researchers and engineers, as it may significantly impact the efficiency and durability of bonded CFRP strengthening systems. This paper presents a comprehensive review of the impact of key characteristics of bonded joints, such as the CFRP modulus, adhesive performance, bond length, adhesive layer thickness, and bond joint geometry, on the bonding performance of CFRP strengthening systems. Additionally, the influences of environmental factors, including elevated and sub-zero temperatures, moisture, corrosion, humidity, wet-dry cycles, ultraviolet radiation, and freeze-thaw cycles on the bond behavior, were also reviewed. By synthesizing and analyzing existing research insights into the effects of reinforcement materials, bond joint design parameters, and environmental factors on bonding performance, this review article attempts to enhance practitioners' understanding of bond behavior in this field and also provides guidance for future research.

Keywords: Review; carbon fiber-reinforced polymer (CFRP); strengthening steel structures; bond behavior; environment influence factors

1 Introduction

Carbon fiber-reinforced polymer (CFRP) composites are highly favored for repairing and strengthening of steel structures due to their exceptional properties, including high specific strength, high specific stiffness, corrosion resistance, and fatigue resistance [1-3]. Nevertheless, the bonding performance and long-term durability of CFRP strengthening systems can face significant challenges due to limitations in the material properties of the strengthening device, variations in bond joint geometries, and the detrimental effects of harsh environmental conditions [4, 5]. As such, this review serves as a valuable reference for future studies by consolidating research advancements in CFRP-strengthening methodologies for steel structures.

The performances of reinforcement materials, including CFRP and adhesive, are the key factors affecting the CFRP-strengthening system. Generally, CFRP with higher mechanical properties exhibits better bond performance when using an identical adhesive [6]. Furthermore, previous studies [7-9] have

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shown that the bond strength, durability, and stiffness of the CFRP-strengthening system are directly affected by the performance of the adhesive [10]. For instance, the bond strengthened was enhanced using linear (brittle) adhesives but lacked sufficient ductile [11], and demonstrated poor resistance to high temperatures. The use of nonlinear (ductile) adhesives resulted in a toughened system after curing, capable of withstanding greater impacts and vibrations [12]. However, the CFRP-strengthening system generally showed relatively lower bond strength and were sensitive to environmental factors such as humidity and temperature [13]. In conclusion, the development of strengthening materials with excellent properties and adaptability is crucial for improving the bond performance of CFRP-strengthening steel structures.

The bond joint forms and the bond methods are crucial factors influencing the bond performance of the CFRP-strengthening system. The geometric shape of adhesive joints directly impacts the bond interface area and stress distribution [14, 15]. The ends of lap joints were chamfered using redundant adhesive to enhance the bond strength [15]. In addition, a larger bond surface area could be provided via increasing the bond length, thereby increasing bond strength [16]. However, research indicates that the bond strength between the CFRP and steel no longer increased beyond a certain bond length [17], and excessive bond lengths may lead to stress concentration and fatigue issues. Therefore, it is crucial to develop an effective predictive model for bond length. Moreover, the thickness of the adhesive layer is a key factor affecting bond performance. An excessively thin adhesive layer may result in insufficient bond strength, while an overly thick adhesive layer could lead to defects [18, 19].

The bond performances of the CFRP-strengthening system deteriorate in adverse environments and exhibit significant durability shortcomings. Previous studies [20-22] indicate that the bond strength decreases with rising temperatures. This is attributed to the changes in adhesive material properties caused by high-temperature conditions, which affect stress distribution at the bond interface. Similarly, the bond interface was corrupted and damaged after being water penetrated in a humid environment, resulting in degradation of the bond performance [23]. In addition, research indicated that UV radiation led to degradation and aging of polymers, reducing material performance [24]. Repeated expansion and contraction of adhesive materials occurred under freeze-thaw and wet-dry cycling conditions, leading to fatigue and damage at the bond interface [25]. To conclude, comprehending the mechanisms by which adverse environmental factors influence bond performance is crucial for ensuring the long-term stability and effectiveness of CFRP-strengthening systems. This understanding can drive the development of bond materials with improved weather resistance and adaptability, thus enhancing the overall performance and durability of the strengthening system.

This study reviews the impact of CFRP modulus, adhesive types, modified traditional adhesives and film adhesive on the bond performances of the CFRP-strengthening system. Next, the influence of geometric configuration and bond parameters of bond joints on the bond performance of CFRP-strengthening steel structures was discussed. The effective bond length predicted models were also summarized. Finally, the bond behavior of the CFRP-strengthening system under complex environmental factors, including elevated and sub-zero temperature, humidity, UV radiation, freeze-thaw cycles, and wet-dry cycles, was evaluated. This study offered investigated guidance for bond behavior of CFRP-strengthening steel structures.

2 Bond behavior between CFRP and steel

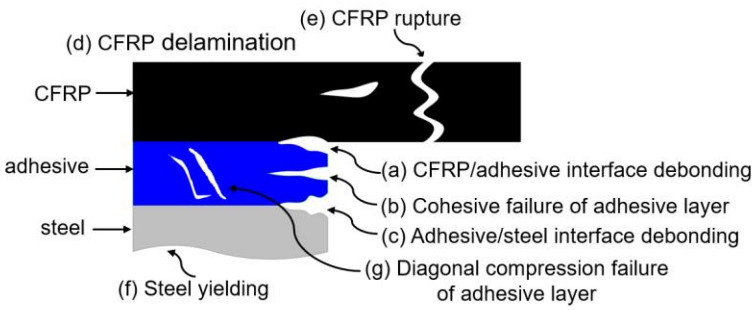


Fig. 1. Failure modes of the CFRP-strengthening system [27].

In recent decades, externally bonded CFRP reinforcement technology has been fully developed in concrete reinforcement and repair. In contrast, the study on steel structures strengthened with CFRP started late, and the understanding of the bond behavior of concrete strengthened with CFRP was only partially applicable to steel structures strengthened with CFRP [26]. Therefore, more investigations are needed to explore the bond behavior between CFRP and steel. Generally, the CFRP-strengthening system was divided into seven failure modes, as shown in **Fig. 1**. Among them, (a) - (c) and (g) are attributed to adhesive failure and are the most common failure modes [2, 27].

2.1 Material parameters

2.1.1 Adhesive property

The adhesive in the CFRP-strengthening system has good resistance to static and dynamic loads and plays an essential role in improving damaged tolerance and quasi-homogeneous stress distribution. However, the adhesive and CFRP not being fully glued due to insufficient adhesive material properties [28]. Therefore, the performance of the adhesive is the main factor affecting the CFRP-strengthening system [10, 29, 30].

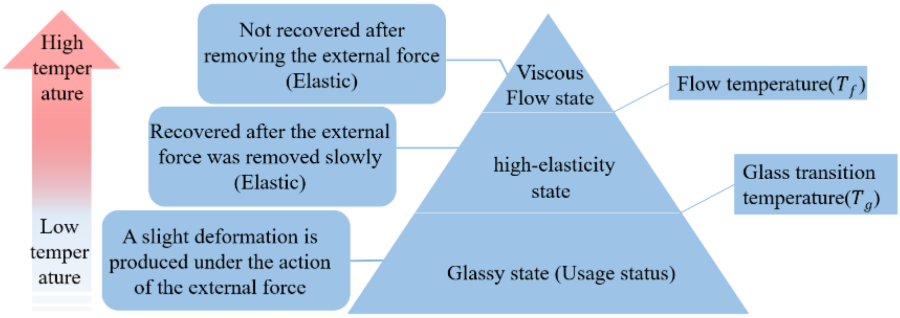


Fig. 2. Three mechanical states of the thermosetting resin at different temperatures.

Generally, the most common adhesive is epoxy resin [31], which has excellent bond properties and corrosion resistance and is a common thermosetting resin bond material widely used in the aerospace, automotive, and civil construction industries. Three mechanical states, including glass state, high-elasticity state, and viscous flow state, were presented to the epoxy resin adhesive under certain stress in different temperature ranges (20℃ to 50℃ is low temperature, and above 50℃ is high temperature), as shown in **Fig. 2**. Previous studies have demonstrated that the epoxy resin adhesive deteriorated and softened rapidly when its serves temperature near the T_g (glass transition temperature, GTT), resulting in the degradation of the bond performance of CFRP-steel bonded joints [9, 32, 33].

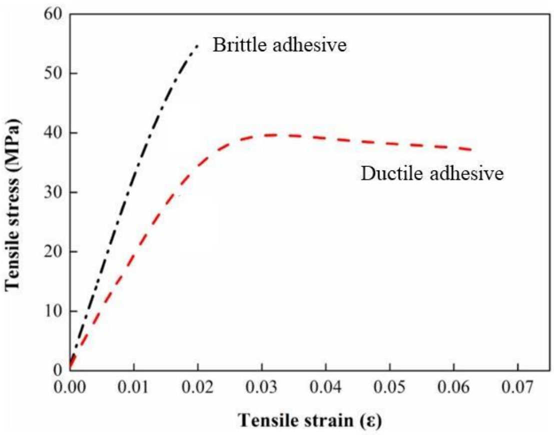


Fig. 3. Stress-strain relationships of ductile and brittle adhesives [26].

The epoxy resin adhesive is classified into brittle (linear) and ductile (non-linear) according to the mechanical properties [18]. **Fig. 3** shows the stress-strain relationships of linear and non-linear epoxy resin adhesive. It was found that the epoxy resin adhesive suitable for high-temperature applications was too brittle, while those suitable for room-temperature applications had low modulus and tensile strength [34], which limited the application in engineering structures. For example, Hosseini [35] found that the bond strength of linear epoxy resin adhesive at room temperature was three times that of non-linear epoxy. The non-linear epoxy resin adhesive with a high GTT (T_g = 56.6℃) was ultimately selected as the adhesive layer since the service temperature of the reinforced structure was 39.1℃. Furthermore, the cross-linking density of the epoxy resin adhesive was decreased under the hygrothermal environment, resulting in a decrease in the T_g [36]. In conclusion, the development of adhesives with both excellent mechanical properties and high GTT has become the focus of the following study.

2.1.2 Modified and untraditional adhesives

The higher short-term CFRP-steel bond capacity and long-term durability could not be satisfied simultaneously. Consequently, modified traditional epoxy adhesives (including carbon nanotubes, nanographene, and nano-silica) and untraditional adhesives (including film adhesive) has become a new investigation direction. Developing nanoparticle-reinforced bonds is one of the most exploratory fields in materials science and engineering [37, 38]. Previous studies [37-39] have revealed that the mechanical properties, bond strength, and durability were significantly heightened by adding nano-fillers into the epoxy resin adhesive. Khoramishad et al. [40] revealed that the adhesive modified by graphene nanoparticles could improve the bond strength of the joint by 34.5% ~ 50.3% at room temperature, while the bond strength decreased when the temperature exceeded 40℃. Dehghan et al. [41] found that the carbon-nanotube (CNT) modified adhesive significantly improved the bond strength at room and elevated temperatures. **Fig. 4** shows the mechanical properties of nano-modified adhesive. The results indicate that the critical mechanical performance indicators of the modified adhesive have been purposefully improved. For instance, Korayem et al. [7, 42] investigated the effect of carbon-nanotube-modified Araldite 2011 adhesives on the bond performance of CFRP-steel interfaces. The results showed that the bond strength of the CFRP-steel joints was significantly improved compared to the unmodified adhesive reinforcement system. However, the reinforcing effect weakened when the bond length exceeded 60mm. This was mainly attributed to the improved the tensile modulus and strength, but decreased ultimate tensile strain, resulting in the mechanical properties of the modified adhesives not being fully utilized beyond a certain bond length. Borrie et al. [26] showed that the bond performance and durability of the CFRP-strengthening system were able to be improved by the CNT-modified Araldite-420 adhesive. Furthermore, it is worth mentioning that Li et al. [8] found that functional nano-SiO2-modified EA could also significantly increase the interfacial bond strength, but the durability of the strengthening system has not been thoroughly studied. However, the cost, time, and dispersion difficulties of CNT-modified adhesive prevented viable industrial applications.

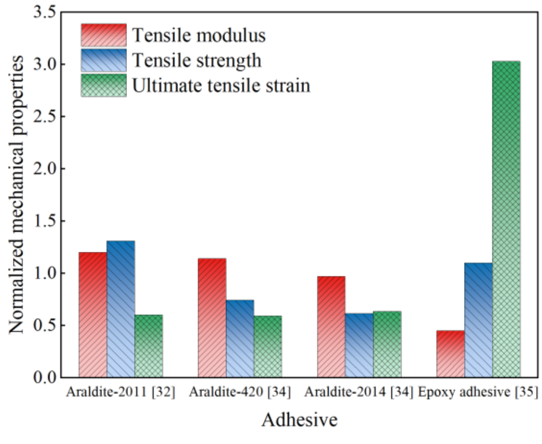
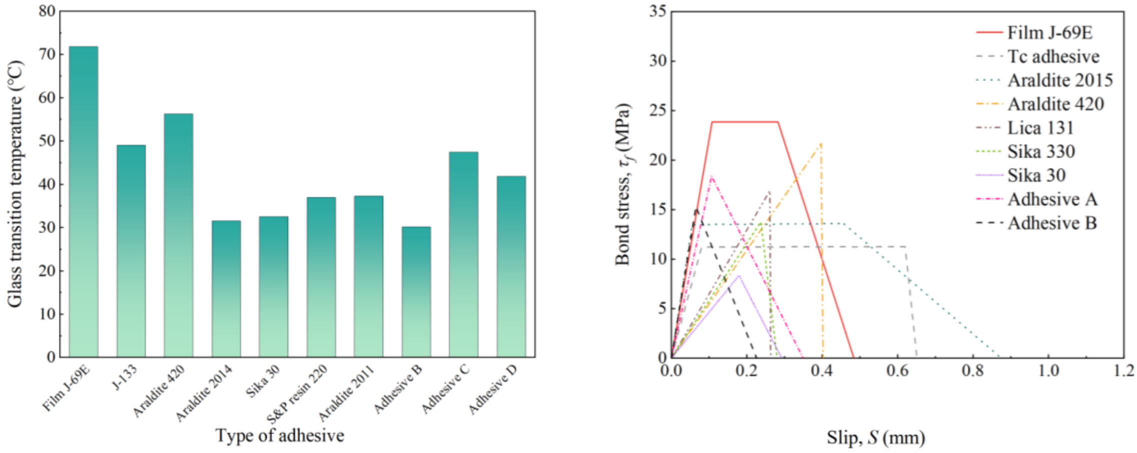


Fig. 4. The normalized mechanical properties of nanometre-modified adhesive on neat adhesive.

Untraditional adhesives, including polyacrylate, polyurethane and film adhesives, were also used in CFRP strengthening systems. Galvez et al. [43] studied the application of the epoxy resin and mixed polyurethane adhesives in the CFRP-strengthening system, and the results showed that the joint had excellent durability and higher reliability due to the post-curing process of the epoxy resin adhesive in the humid environment. The post-curing does not occur in the mixed polyurethane adhesive, resulting in the bond strength degenerating in the erosive environment. However, both adhesives were able to maintain adequate strength after completing the degradation process. Unfortunately, the internal structures of the polyurethane adhesive were prone to decomposition in high temperatures and humid environments, resulting in catastrophic degradation of its bond strength and limiting their engineering application. Ke et al. [17] investigated a novel film adhesive with high GTT, which exhibited higher bond stress and elevated temperature resistance than traditional epoxy adhesive, as shown in **Fig. 5**.

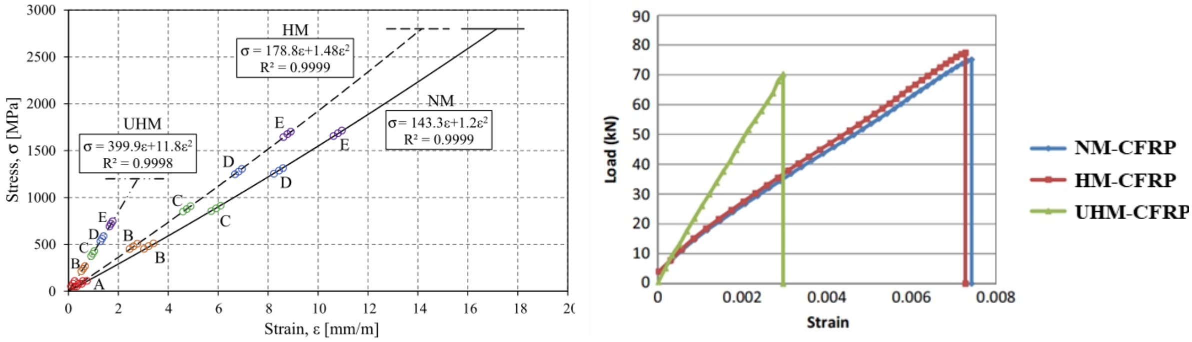


(a) (b)

Fig. 5. GTT temperature and bond-slip relationship of the film and traditional adhesives: a) GTT temperatures, b) bond-slip relationship [17].

In summary, traditional epoxy resin adhesives were challenging in meeting bond strength and ductile requirements in harsh environments simultaneously. Moreover, the engineering application of nano-modified epoxy adhesives has been hindered. Therefore, further research should focus on developing nano-modified adhesives that can improve the bond performance of CFRP-strengthening systems and have simple construction properties. Similarly, film adhesives can improve the CFRP-strengthening system bond performance and meet the expected environmental erosion resistance. Therefore, developing a more comprehensive adhesive will become essential to future research.

2.1.3 CFRP property



(a) (b)

Fig. 6. CFRP and CFRP/steel double strap joints mechanical properties for NM, HM, UHM: (a) stress-strain relationship, and (b) ultimate load vs. ultimate strain [44,48].

Previous studies have shown that the CFRP modulus is one of the key parameters affecting the bond performance of the CFRP-strengthening system. In general, the CFRP modulus was divided into normal modulus (NM), high modulus (HM), and ultra-high modulus (UHM) [44]. **Fig. 6** (a) shows the mechanical performance of three types of CFRP modulus in the different strain levels. It can be seen that the stress-strain relationship of CFRP exhibits nonlinearity, which is attributed to interfacial debonding between the fibers and matrix, fiber breakage, matrix yielding, and fracture. Moreover, HM and UHM-CFRP were favored by researchers in the field of civil engineering, which attributed to the lower fracture strain of higher modulus CFRP [45, 46]. The experimental and numerical studies have shown that the stress concentration of the CFRP-steel bond ending was reduced using HM modulus CFRP, resulting in CFRP rupture becoming the primary failure mode of the strengthening system [6,47]. **Fig. 6** (b) shows the ultimate load vs. ultimate strain for three different CFRP/steel strap joints. It was found that the maximum load-carrying capacity of the UHM-CFRP/steel strap joints was relatively high compared with the specimens made of NM-CFRP. However, specimens with UHM-CFRP modulus showed a significant decrease in maximum failure force and strain, attributed to the lower tensile strength and ultimate strain of UHM-CFRP.

Previous studies have shown that the bond performance the CFRP strengthening system was heightened using different layers CFRP sheets. A. Al-Zubaidy et al. [49] investigated the evolution of dynamic bond strength of CFRP sheet-strengthened steel structures under direct tension. The results indicated that bonding with three layers of CFRP sheets exhibited higher bond strength than bonding with one layer. However, the CFRP-strengthened system bonding with multiple layers of CFRP sheets was more susceptible to delamination failure. Tang et al. [50] found that the distribution of internal strain within the CFRP sheet was affected by increasing the number of CFRP sheet layers, leading to asynchronous slip between different layers, which affected the distribution of shear stress. The CFRP strengthening system was prone to debonding failure at the ends. Wang et al. [51] demonstrated that the debonding failure of the CFRP strengthened system could be effectively suppressed by anchoring at the ends of CFRP sheet-strengthened damaged steel structures. Elkhabeery et al. [52] found that the influence of CFRP sheet modulus on the ultimate bearing capacity of I-beams strengthened with CFRP sheet could be ignored. Hmidan et al. [53] found that the number of CFRP sheet layers had a more significant impact on reducing the stress intensity factor at the crack tip than the CFRP modulus. From the above, it is clear that the number of layers should be determined when strengthening steel structures with CFRP fabric. In contrast, when strengthening with CFRP plates, the elastic modulus has a more significant impact on extending the fatigue life of the CFRP strengthening system. Lepretre [54] found that the fatigue life of an open-hole steel structure increased 2.27 times after reinforcing by HM-CFRP plate. The fatigue life of an open-hole steel plate with a 30% damage level increased three times when reinforced with UHM-CFRP plate [55, 56]. However, the cost of HM and UHM-CFRP, which had excellent strengthened performance, was relatively high, resulting in the laboratory investigating stage and not being popular in practical engineering. Therefore, researchers have used prestressed CFRP plate to strengthen damaged steel structures and achieved good research results, effectively verified in engineering applications. A numerical method was conducted by Lepretre et al. [57], demonstrating that the fatigue life growth rate of cracked steel structure strengthened by high-prestress NM-CFRP plate was similar to the strength of UHM-CFRP plate. Furthermore, the fatigue life was further extended by increasing the width of the NM-CFRP laminate and applying prestressing [58].

In conclusion, the requirements for the load-bearing capacity of CFRP strengthening systems could be met under quasi-static loading using NM- and HM-CFRP. Moreover, the service life of the damaged steel structures strengthened by prestressed NM-CFRP and UHM-CFRP plates could be significantly extended and have potential application prospects in practical engineering.

2.2 Bond joint geometries

2.2.1 Bond length

Bond length is one of the important factors in determining the bond strength of the CFRP-strengthening system. Previous studies [13, 59, 60] revealed that the bond strength between CFRP and steel will stay the same when the bond length reaches a maximum value, defined as effective bond length. Therefore, it is essential to determine a reasonable bond length to avoid material waste and achieve the ultimate bond strength of the strengthening system.

The material parameters affected the effective bond length of the strengthening system. For example, Phan et al. [61] demonstrated that the effective bond length depended on the type of CFRP and adhesive rather than the steel strength. Similarly, two kinds of CFRP plates with different carbon fiber stiffness for the bond strength of the CFRP-strengthening system were studied by J. Davd et al.

[62] and demonstrated that the effective bond length of CFRP plate with higher carbon fiber stiffness was 60 mm, while the bond strength of CFRP plate with lower carbon fiber stiffness was not fully utilized when the bond length was 60 mm, indicating that the CFRP plate with higher stiffness had lower effective bond length. In addition, the effective bond length was affected by adhesive type as well. The investigation revealed that the tough adhesive had a more significant ultimate strain, leading to the effective bond length being more critical than the brittle adhesive [63].

To better predict the bond behavior and performance of the CFRP-strengthening system, scholars have proposed effective bond length prediction models based on fracture mechanics and stress analysis, summarized in **Table 1**. A database of the effective bond length based on the existing literature was established by Hu et al. [64] and demonstrated that the Xia and Teng model based on fracture mechanics had a better prediction effect on the test results, while it was still not safe. In addition, the existing effective bond length models were mainly based on empirical formulas and tested data and did not apply to all bond materials. Therefore, it is recommended that targeted experimental research on CFRP-strengthening systems be carried in the future to obtain more accurate effective bond length test results and improve the effective bond length calculation method.

Table 1. Summary of the effective bond length prediction models

Author	Joint forms	adhesive	Type of adhesives	Key parameters prediction equation	Failure modes
Xia & Teng [65]	Single-lap joint	EP	linear	$L_e = \frac{\sqrt{62}\pi}{1.6 f_a \sqrt{E_p t_p}} (\frac{f_a}{G_a})^{0.28} t_a^{0.135}$	(b)
He [19]		Araldite-2015	non-linear	$L_e = 45\left(\frac{E_p}{f_a \varepsilon_{eq}}\right)^{0.4} \varepsilon_{eq}$ $\varepsilon_{eq} = 0.5(\varepsilon_e + \varepsilon_p)$	(b)
Bocciarelli [66]	Double-lap joint	Sika-30	linear	$L_e = 5.54\sqrt{\frac{\beta}{\beta+1} \cdot E_p t_p \frac{2.71828 t_a}{G_a}}$ $\beta = \frac{b_s t_s E_s}{2 b_p t_p E_p}$	(c)
Bocciarelli [67]		Sika-30	linear	$L_e = \frac{5}{\lambda}$ $\lambda = \sqrt{\frac{G_a b_a}{t_a}(\frac{1}{E_p t_p b_p} + \frac{2}{E_s t_s b_s})}$	(c)
Hart-Smith [68]		adhesive-A	linear	$L_e = \frac{F}{2\tau_p} + \frac{2}{\lambda}, \lambda = \sqrt{\frac{G_a}{t_a}(\frac{1}{E_p t_p} + \frac{2}{E_s t_s})}$ $F = b_f \min\{F_1, F_2\}$	(c)
		adhesive-B	non-linear	$F_1 = \sqrt{4\tau_f t_a \varepsilon_{eq} E_s t_s (1 + \frac{E_s t_s}{2E_p t_p})}, E_s t_s < 2E_p t_p$ $F_2 = \sqrt{8\tau_f t_a \varepsilon_{eq} E_s t_s (1 + \frac{E_s t_s}{2E_p t_p})}, E_s t_s \geq 2E_p t_p$	(c)
Dehghani [69]		EP	non-linear	$L_e = 3.5\sqrt{\frac{E_p t_p t_a}{G_a}}$	(a) + (c)

Note: L_e is the effective bond length; G, E, t, and b represent the shear modulus, tensile modulus, thickness, width, respectively; P, a, and s represent the CFRP, adhesive, and steel, respectively; f_a is the tensile strength of the adhesive; F is the test load value; τ_f is the maximum shear stress; ε_e and ε_p represent the elastic and plastic strain of the adhesive, respectively; τ_p is the plastic adhesive shear stress. The (a), (b), and (c) represent the CFRP/adhesive interface debonding, cohesive failure of adhesive layer, and adhesive/steel interface debonding, respectively.

2.2.2 Adhesive layer thickness

The adhesive layer thickness is one of the key factors affecting the bond strength of CFRP-steel joints, and it is an unresolved issue with no consensus reached so far. Previous studies have shown that the ultimate load of CFRP-steel single-lap joints increased with adhesive layer thickness for nonlinear adhesives, while the linear adhesive exhibited characteristics independent of the adhesive layer thickness, as shown in **Fig. 7**. In addition, Wang et al. [18] investigated the bond behavior between CFRP laminates and steel by single-lap shear tests, and the results showed that increasing the adhesive layer thickness led to increases in interface ultimate load, initial slip, and fracture energy. In addition, the failure mode of the CFRP-strengthening system would change due to the different adhesive layer thicknesses. When the adhesive layer thickness was 0.5 mm, 1 mm, and 1.5 mm, the failure modes correspond to CFRP delamination, a combination of cohesive failure and CFRP delamination, and mixed failure models of partial fiber fracture and CFRP delamination, respectively. Similarly, Li et al. [70] carried out double-lap tensile tests to study the effect of adhesive layer thickness on the bond performance of CFRP plates reinforcing corroded steel plates, and the results showed that the ultimate load increased with adhesive layer thickness. In particular, the interface bond strength of the uncorroded steel sheet was susceptible to changes in adhesive layer thickness. Furthermore, as the adhesive layer thickness increased from 0.5 mm to 1.5 mm and then to 2.0 mm, the failure mode of the CFRP-strengthening system changed from steel/adhesive interface failure to CFRP/adhesive interface failure and then to a mixed failure mode of CFRP/adhesive interface failure and CFRP delamination. The interface fracture energy of CFRP-steel double-lap specimens was investigated using numerical simulation by Chandrathilaka et al. [71], demonstrating that it increased with adhesive layer thickness, resulting in a more stable bond. Wang et al. [72] found that when using Araldite2015 ductile adhesive as the adhesive layer, the results of single-lap shear tests showed that the bond strength increased slightly with the adhesive layer thickness increased from 0.5 mm to 1.0 mm, and the failure mode changed from cohesive failure to a combination of cohesive failure and CFRP delamination.

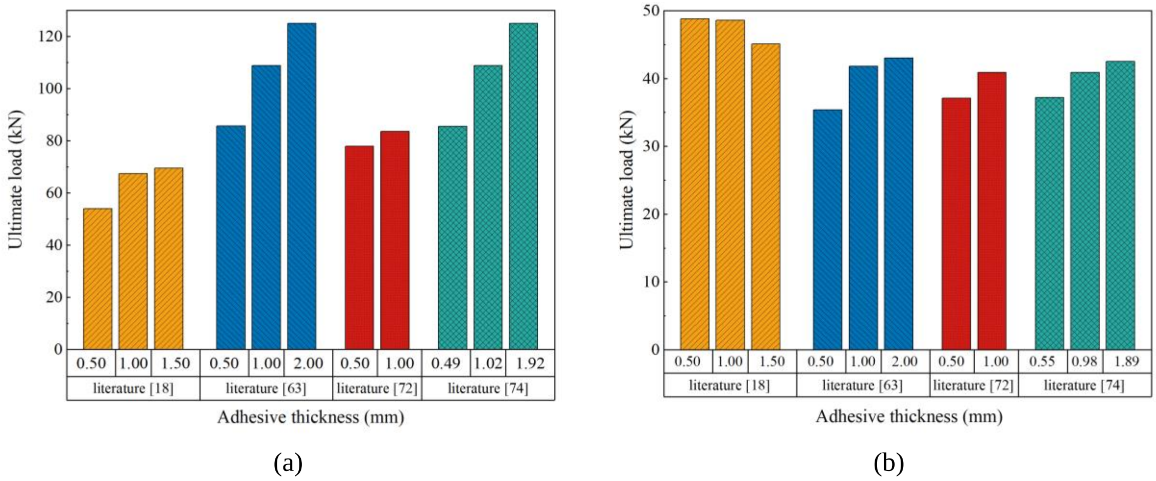


Fig. 7. Ultimate load of CFRP-steel single-lap joints under different adhesive layer thicknesses: (a) nonlinear adhesive, (b) linear adhesive.

The influence of adhesive layer thickness on the bond strength of CFRP-steel joints is negligible for linear adhesive. Pang et al. [73] conducted single-lap shear tests on CFRP plates bonded with two brittle adhesives, and the results showed that as the adhesive thickness increased from 0.5 mm to 2 mm, the interface bond strength only increased by 12%. The failure mode of the CFRP-steel joint remained CFRP delamination regardless of adhesive layer thickness. Similarly, Wang et al. [74] studied the bond behavior of Sikadur-30 brittle adhesive in single- and double-lap shear tests. The results showed that as the adhesive thickness increased from 0.5 mm to 1 mm, the interface ultimate load only increased by about 10%. The strengthening system failure mode remained cohesive failure regardless of adhesive layer thickness and joint type. Mohabeddine et al. [75] found that the influence of adhesive layer thickness on the bond strength of CFRP-steel double-lap joints was negligible. However, the failure model of the strengthening system was dominated by CFRP delamination when the adhesive layer thickness of S&P HP220 brittle adhesive was 1 mm, while the cohesive failure of the adhesive layer became dominant when the adhesive thickness was 0.6 mm. In addition, Xie et al. [76] conducted double-lap tensile tests on CFRP-steel joints, and the results showed that the interface ultimate load at adhesive layer thicknesses of 0.5 mm and 1 mm were 57.37kN and 64.43kN, respectively, an increase of about 12.3%. When the adhesive layer thickness changed from 1 mm to 0.5 mm, the failure mode changed from cohesive failure to interface debonding failure.

In conclusion, the bond strength and interface ultimate load increased with adhesive layer thickness using ductile adhesive as the adhesive layer, and the failure mode also changed accordingly. However, the influence of adhesive layer thickness on CFRP-steel bond strength was negligible when using brittle adhesive as the adhesive layer. Furthermore, there is some controversy regarding the impact of adhesive layer thickness on the failure mode. Therefore, selecting a suitable adhesive type and adhesive layer thickness is necessary to obtain optimal bond properties and service performance.

2.2.3 Bond joint geometry

The delamination failure of the CFRP-strengthening system often initiates from the adhesive end of the CFRP (as shown in **Fig. 8**), which plays a crucial role in the success of reinforcement techniques [40, 77]. Therefore, the research has shifted towards improving the debonding resistance at the bond joint end using appropriate geometric configurations.

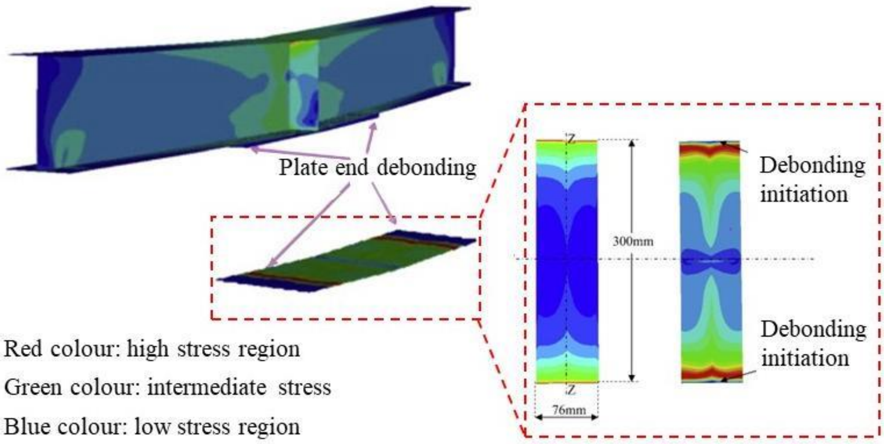


Fig. 8. Finite element simulation of debonding at the end of CFRP steel [77].

Kamruzzaman et al. [40] investigated the fatigue performance of CFRP-reinforced I-beams with rectangular, trapezoidal, semi-circular, and semi-elliptical bond joint ends, as shown in **Fig. 9** (a). The results showed a 54% increase in fatigue life using trapezoidal bond joint ends compared to rectangular ones. This is mainly attributed to the stress concentration being effectively reduced by the trapezoidal end, resulting in lower bond joint end deflection, strain rate, and enhanced stiffness. Similarly, Kowal et al. [15] conducted experimental and numerical studies on the impact of different end geometric configurations on the bond performance of CFRP laminates strengthened with steel. The results indicated that the load-carrying capacity was significantly increased by beveling the bond joint end into a trapezoidal shape. In addition, the bond joint ends were anchored as an effective method to prevent early delamination failure in the strengthening system. Currently, most studies focus on prestressing CFRP using mechanical anchoring methods and fixation [78-80]. Yang et al. [78] investigated the bond behavior between CFRP and steel after mechanical anchoring, as shown in **Fig. 9** (b). The results indicated that the bond joint reached its maximum load-carrying capacity when the anchoring device was installed near the CFRP end. Li et al. [81] conducted experiments on prestressed CFRP-reinforced notched steel beams with a mechanical anchoring system, and the results showed that the mechanical anchoring system prevented prestress loss and delayed debonding failure in the reinforced steel beams. However, mechanical anchoring has disadvantages, such as construction complexity, susceptibility to corrosion, and high cost. Researchers have explored the impact of U-wrap clamps on the delamination load-carrying capacity of CFRP-strengthening systems [82, 83]. Reference [82] pointed out that delamination failure of the strengthening system was prevented by U-wrap clamps but caused uneven stress distribution. In conclusion, mechanical anchoring of the CFRP bond end was the commonly used anchoring method. However, the CFRP was covered after anchoring, making it a concealed structure, resulting in difficulty in accurately measuring shear stresses and CFRP tensile strain distribution at the bond end using experimental methods. Therefore, further research was needed to optimize bond joint end anchoring systems in the future.

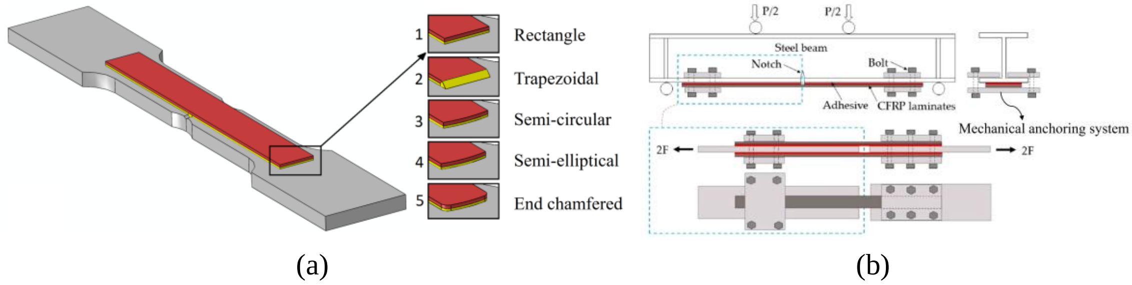


Fig. 9. CFRP end bond geometry: (a) bond forms [40], (b) mechanical anchoring [84].

2.3 Surface condition of steel structures

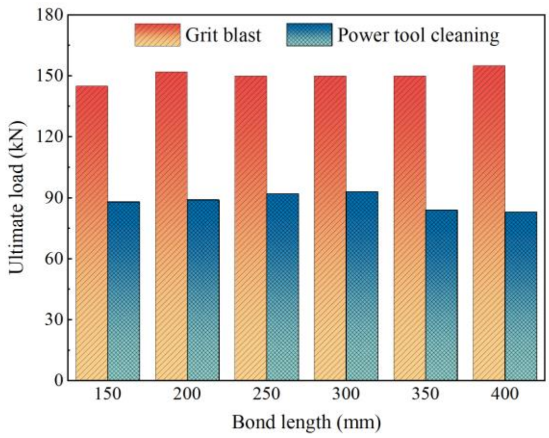


Fig. 10. Effect of surface preparation for the ultimate load of CFRP-steel double lap joints [83].

The bond performance of CFRP strengthening systems is related to the roughness of the steel structure surface. Increasing the roughness of the steel structure surface can enhance the contact area of the adhesive, thereby increasing the surface energy between CFRP and steel [33]. Techniques for enhancing the roughness of steel structure surfaces include mechanical polishing and grit blast [59, 85-87]. Previous studies [85, 88 ,89] have indicated that grit blast was the most effective method for enhancing the roughness of steel structure surfaces. Russian et al [85] investigated the bond performance between CFRP and steel structures, focusing on surface condition with mechanical polishing and grit blast in double lap joints. The results showed that the steel structure with grit blast exhibited a greater ultimate load than those with mechanical polishing, as shown in **Fig. 10**. Silva et al. [33] found that the maximum bond stress of CFRP strengthening systems increased by 18.4% and 34.7% after sand and steel grit blasts compared to specimens with untreated surface, respectively. Cai et al. [90] evaluated the effect of different surface preparation techniques on the bond behavior between CFRP and corroded steel plates. The results indicated that mechanical polishing technique is suitable for steel structures with early-stage corrosion, but it is not recommended for steel structures with severe pitting corrosion. This is because residual rust and secondary rusting after mechanical polishing make it more difficult for the steel structures to bond tightly with the adhesive. In addition, the grit blast technique is superior to acid solvent and disk sander techniques [90]. This is because grit blast technique not only aided in rust removal but also helped to ground-adjust the depressions on the surface of the steel structures, enhancing the adhesive’s wetting and diffusivity. Similarly, Ou et al. [91] found that the surface of steel structure specimens prepared with mechanical polishing exhibited undulating depressions with significant dispersion. Conversely, the surface condition with grit blast exhibited uniform and independent depressions with a higher roughness. Liu et al. [92] demonstrated that grit blast of steel structure surfaces provided a greater coefficient of friction resistance compared to corner grinding (mechanical polishing technique). The reliability indices of roughness were closer to the target reliability, indicating that grit blast could consistently enhance the bonding performance of CFRP strengthening systems. However, the grit blast generated a large amount of dust, and some lead elements remain after gritting blast, posing a severe environmental hazard [85]. Therefore, when employing grit blast technique, it is necessary to assess the operational environment to avoid the dispersion of residual pollutants, which could pose risks to health and the environment.

The surface chemical preparation of steel structures using silane coupling agents is also an effective technique to enhance the bonding performance of CFRP strengthening systems. References [91, 93, 94] indicated that silane coupling agents can form chemical bonds on the surface of steel structures, enhancing the bonding performance between CFRP and steel structures. Yu et al. [91] compared the mechanical properties of CFRP-corroded steel structures double lap joints with and without silane coupling agents. The results showed that the bond strength of specimens with silane coupling agents was 4% higher than that of specimens without them, indicating a modest improvement. This is mainly attributed to the fact that the enhancement effect of silane coupling agents is highly dependent on the surface cleanliness of the steel structures. The surface contamination has not been thoroughly removed, silane coupling agents may not effectively react with the steel structure surface, leading to a non-significant improvement in bond performance.

3 Environmental influence factors

One of the main limitations of the widespread application of CFRP reinforcement technology is the degradation of mechanical properties and durability of CFRP-steel interface in various adverse. Most researchers deemed the most important influence on the CFRP-strengthening system was the elevated temperature and humidity. This is because the CFRP-steel bond interface was the weak link, and the adhesive performance will degrade significantly after long-term exposure to the two different settings. In addition, some factors like freeze-thaw/sub-zero temperature, moisture, and ultraviolet radiation may also have slightly detrimental effects on the strengthening system [84]. **Fig. 11** briefly shows the action mechanism of corrosive environment factors on CFRP-strengthened steel structures. The effects of elevated/sub-zero temperature, moisture, the freeze-thaw, ultraviolet radiation, corrosion and combination of environments (hygro-thermal and wet/dry cycle) were introduced.

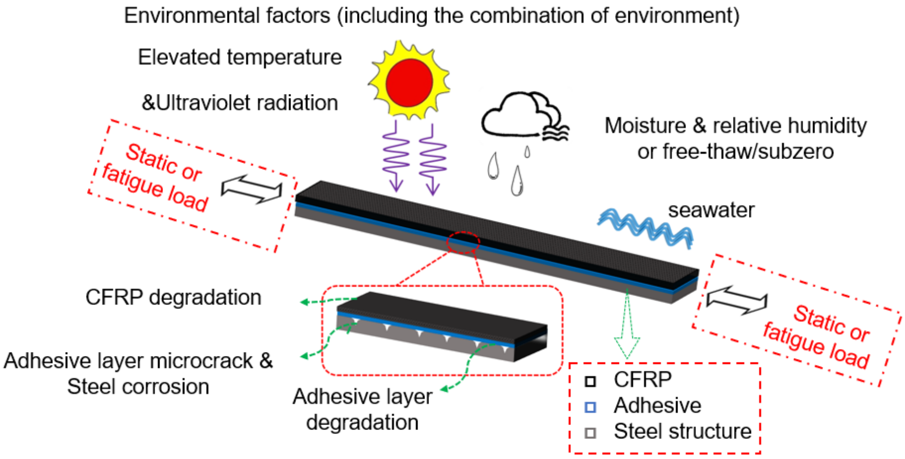


Fig. 11. The effect of environmental factors on CFRP-strengthened steel structures.

3.1 Elevated and sub-zero temperatures

3.1.1 Elevated temperature

The modulus and properties of the epoxy resin that belongs to the polymer materials with lower cross-linking density were reduced at the elevated temperature [21, 22, 95]. Li et al. [96] reported that the bond strength of the CFRP-strengthening system had a minor decrease at the high temperature but below 90℃. In addition, the elastic properties of epoxy adhesive degradation could be characterized by glass transition temperature (GTT). Once beyond the GTT, the polymer will change from a glass state to a high elastic state, and its strength and stiffness will deteriorate rapidly, resulting in the decline of bond performances of the strengthening system [95, 97]. In addition, the mechanical properties such as tensile strength, elastic modulus, and fracture toughness decreased with the rise of ambient temperature, and the degradation rates of different types of adhesives were different [55, 98, 99]. The existing literature [21] showed that the GTT of numerous building adhesives was below 50℃, resulting in the deterioration of bond strength and stiffness of CFRP-steel at elevated so that the elevated temperature resistance performance of the strengthening system was severely insufficient [95, 100].

The bond behavior and failure mode of the CFRP-strengthening system were closely related to the epoxy adhesive [10, 99, 101]. Bai et al. [102] reported that the stiffness and strength of CFRP-steel bond joints were reduced by approximately 80% when the temperature was close to or higher than the GTT of the epoxy adhesive. Similarly, Korayem et al. [103] demonstrated that the failure mode of CFRP-steel bond joints changed from CFRP/adhesive interface failure to steel/adhesive interface failure and turned to adhesive cohesive failure, ultimately with the rise of temperature. Nguyen [21] found that the failure modes of the wet-laid CFRP-steel bond joints changed from CFRP debonding failure (20℃) to interfacial bond failure (beyond 40℃). In addition, their investigation showed that the bond strength decreased by about 15%, 50%, and 80%, corresponding to the temperature achieved in the GTT, higher the GTT 10℃ and 20℃, respectively. Meanwhile, an interesting result was that post-curing improved the bond strength of the CFRP-strengthening system at medium and elevated temperatures [104]. Similarly, He et al. [9] demonstrated that the bond strength decreased by 10% and 70%, corresponding to temperatures lower than the GTT 15℃ and beyond 15℃, respectively. The failure mode changed from CFRP delamination failure at room temperature to steel/adhesive interface failure at elevated temperature. Moreover, they proposed a nominalized bond strength degradation model at high temperatures, as shown in **Fig. 12**. It demonstrated that the bond strength of most adhesives showed a gradual decline trend from 20℃ below the GTT temperature. Therefore, the aging effect of elevated temperature on the strengthening system should not be overlooked, and further research should be conducted to propose appropriate solutions.

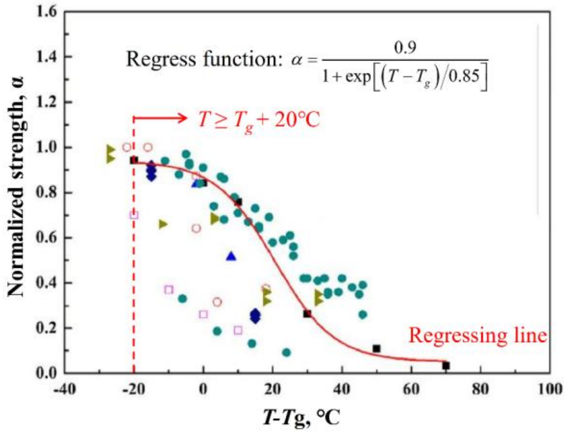
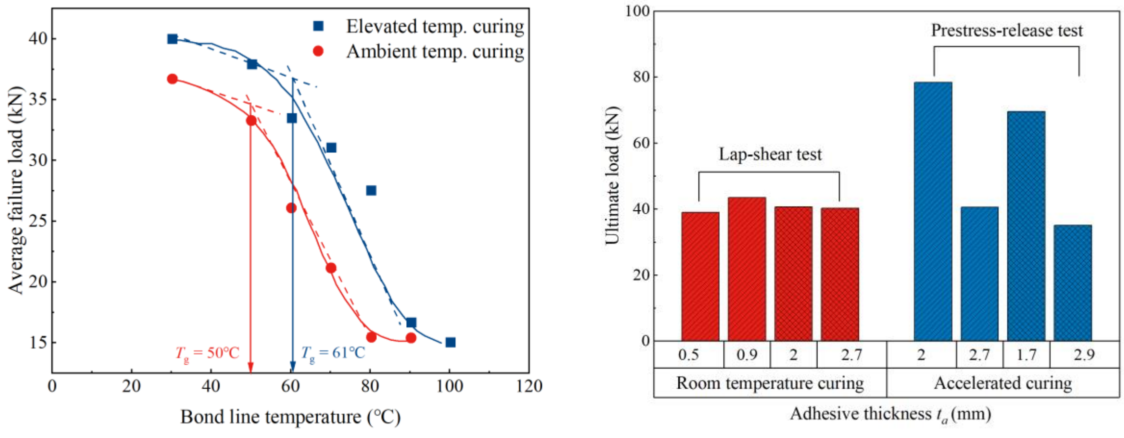


Fig. 12. Normalized bond strength vs. (T-Tg) [10].

The high-temperature cured CFRP-steel bond joints can effectively reduce the bond performance. It was reported that the bond strength of epoxy adhesive at medium and high temperatures was improved significantly under elevated temperature curing [104]. Similarly, Chandrathilaka et al. [20] demonstrated that high-temperature curing caused the adhesive to reach the GTT, as shown in **Fig. 13** (a), resulting in lower degradation of the bond strength at the CFRP-steel interface under elevated temperature service conditions. In addition, Hosseini et al. [11] demonstrated that the bond strength of CFRP-steel shear joint could be significantly improved by elevated temperature accelerated curing at a small adhesive thickness. **Fig. 13** (b) shows the ultimate load of the CFRP-strengthening system under room and elevated temperature accelerated curing. The results show that the strength of the strengthening system accelerated by high-temperature curing increased by about 50% under the identical adhesive thickness. When the bond strength of lap-joint specimens with smaller adhesive layer thickness was measured at elevated temperature, it approached the bond strength of lap-joints with larger adhesive layer thickness cured at room temperature. Therefore, the high-temperature curing of the CFRP-strengthening system will help maintain the stable performance of the strengthening system under elevated temperature environments.



(a) (b)

Fig. 13. GTT and bond strength of the CFRP-strengthening system under high-temperature curing: (a) GTT of CFRP-steel joint [20], (b) ultimate load for different adhesive thicknesses under different curing conditions [11].

3.1.2 Sub-zero temperature

The CFRP-strengthening system was also exposed to the extreme-subzero environment, but the investigation on this aspect is quite scarce. The current studies mainly focus on the influence of sub-zero temperatures on the fluidity of adhesive. Al-Shawarf et al. [105,106] used non-linear finite element simulations to analyze the bond behavior of three commercial adhesives (Araldite 420A/B, MBrace Saturant, Sikadur-30) under extreme conditions (-40 ℃). The results showed that interface debonding was the primary failure mode. The failure load of the CFRP-strengthening system using Araldite 420A/B increased by 103.02% (-40 ℃) and 100.73% (-20 ℃), while the other two adhesives decreased by 39.54% and 70.13% in the -40 ℃ environment, respectively. In addition, Al-Shawarf [107] investigated the bond properties of normal modulus (130GPa) and ultra-high modulus (530GPa) wet laid CFRP at -40 ℃ and demonstrated that the failure mode of normal modulus was controlled by adhesive, while the other was owned by carbon fiber. The ultra-high modulus CFRP was more resistant to extreme-subzero erosion. Similarly, the bond performance of high modulus CFRP with strengthening steel bridge under cold temperature (average -18°C) was studied by Yoshitake et al. [108], and demonstrated that the high modulus CFRP laminates were firmly bonded to the steel beam although under cold temperature.

3.2 Moisture

The moisture can affect the curing reaction of the adhesive and form a water film at the bond interface, reducing the interfacial bond strength. The influence of moisture on the thermos-mechanical properties of epoxy was studied by Pedro Galvez et al. [109], and it was shown that moisture was mainly absorbed in the form of bound water, resulting in the expansion and plasticization of the epoxy resin. In addition, the moisture penetrated the interface between the adhesive and substrate via adsorption, resulting in decreased joint performance. As shown in **Fig. 14**, the area between the adhesive and the CFRP and steel substrates was reduced with the increase in interface moisture content after water penetration into the bond interface, leading to a decrease in bond strength. Additionally, the adhesive was expanded after water entered the adhesive, and the bound water was deformed due to the restriction of the steel substrate, generating a normal force and reducing the energy required for bond failure. Similarly, Heshmati et al. [110] found that the moisture significantly reduced the stiffness and strength of the adhesive, reducing the bond strength. The moisture diffusion and strength degradation of epoxy adhesives in distilled water and seawater were studied by Han et al. [111], and they found that the water could significantly decrease the bond strength. The strength degradation was more significant when the degradation of joint stiffness and strength was mainly attributed to the degradation of adhesive. In conclusion, effective measures should be taken to avoid moisture erosion of the CFRP-strengthening system.

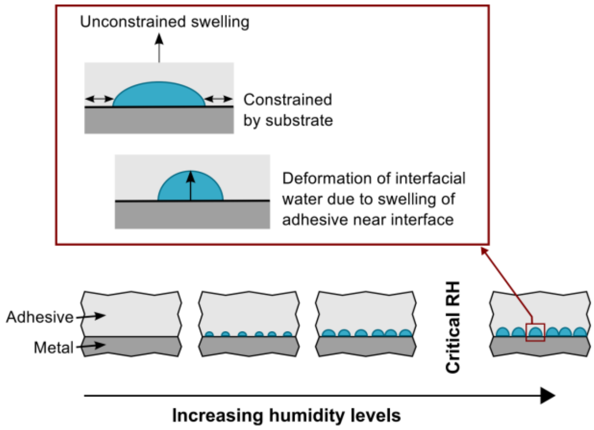


Fig. 14. Schematic diagram of bonding loss after water immersion into the bonding interface [112].

The CFRP-strengthening system was susceptible to salt fog and relative humidity. The adhesive will appear soft in a humid environment, resulting in the reduction of the bond strength. Yong et al. [29] investigated the influence of a salt fog environment on the performance degradation of CFRP-steel joints and found that the corrosion products deposed over the components and acted as the electric bridge, resulting in the damage of the carbon fiber-matrix interface in the CFRP laminates, thus the reinforcement performance of the CFRP has not been fully utilized. Yu et al. [91] studied the bond strength of a CFRP-strengthening system exposed to salt fog and elevated relative humidity and found that a high-modulus CFRP sheet was more susceptible to relative humidity. In addition, the influence of the relative humidity on the GTT of epoxy adhesive at room temperature was studied by Lettieri et al. [23], who found that the higher the relative humidity, the higher the water absorption rate. In particular, more moisture was absorbed when the relative humidity was above 75%, resulting in the plasticization effect of the adhesive and significantly reducing the GTT of the epoxy resin. Heshmati et al. [113] demonstrated that the moisture content under steam conditions (relative humidity 95%) of the CFRP-strengthening system was higher than that under soaking conditions at room temperature, indicating that high temperature and humidity environments have a higher degree of damage to the bond joints. Therefore, it is one of the critical factors for improving bond performance to control moisture and humidity in the environment.

3.3 Corrosion

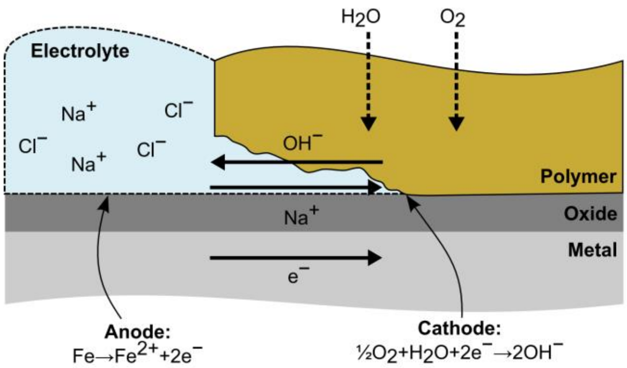


Fig. 15. Schematic diagram of effect of cathodic corrosion on the bonding interface [116].

Generally, CFRP materials exhibit excellent resistance to corrosion. However, when CFRP strengthening systems were exposed to marine environments, their bond performance was inevitably subject to degradation [114]. This is primarily due to chloride ions and other components in seawater penetrating the CFRP/steel bond interface, corroding the adhesive, and decreasing the strength and stiffness of the strengthening system. **Fig. 15** illustrates a schematic representation of the electrochemical corrosion of the adhesive layer in the CFRP strengthening system after the infiltration of electrolytes. Oxidation-reduction reactions occurred at the cathode (adhesive) after the infiltration of electrolytes into the bond interface, generating OH^- and increasing the PH value at the bond interface [115]. To compensate for the charge consumed by the reaction at the cathode, the metal dissolution at the anode (steel substrate) produced cations and charged them, which were transported to the cathode. This process caused the adhesive to delaminate and expand, gradually debonding from the CFRP and steel substrates.

Kim et al. [117] demonstrated that the coupled reactions between the anode and cathode lead to the accumulation of hydrated ferric oxide at the bond interface after the electrolytes in seawater infiltrate the CFRP strengthening system. This resulted in a decrease in the ultimate bearing capacity of the CFRP strengthening system, ultimately leading to cohesive failure. Nguyen et al. [114] studies showed that the strength and stiffness of CFRP-steel double-lap joints decreased significantly one year after exposure to seawater. Batuwitage et al. [118] investigated the degradation of the bond performance of CFRP-steel double-lap joints immersed in saltwater employing an accelerated corrosion method. The results indicated that the longer the specimens were exposed to saltwater, the more significant the reduction in the stiffness of the CFRP strengthening system. However, Kabir et al. [119] demonstrated that the impact of seawater corrosion on the bond strength of lap joints can be mitigated using non-linear adhesives to bond CFRP to strengthen marine steel structures. Moreover, Wu et al. [120] demonstrated that a glass fiber layer embedded in the adhesive layer could protect the bond layer from galvanic reactions induced by seawater erosion, thereby reducing the negative impact on the bond performance. Dawood et al. [94] have shown that it is one effective method for improving the corrosion resistance of CFRP-steel lap joints to introduce silane coupling agents into the adhesive. Tavakkolizadeh et al. [121] have demonstrated that the rate of galvanic corrosion was reduced by coating CFRP and steel substrates with an epoxy layer. In conclusion, the corrosion of CFRP strengthening systems exposed to marine environments should be mitigated or prevented by effective measures, ensuring that the strengthened structure maintains sufficient bonding performance during service.

3.4 Humidity and wet-dry cycles

The bond performance of the CFRP strengthening system underwent severe degradation under the combined effect of temperature and humidity (Hygrothermal). This is mainly attributed to the mechanical properties of epoxy resin adhesive, which deteriorated severely [122]. **Fig. 16** shows the relationship between stress and strain of the adhesive matrix in the natural environment. The results indicated that the ultimate stress and the slope of these curves decreased as the exposure time increased in a dual environment of humidity and temperature. Nguyen et al. [114] investigated the strength and stiffness degradation law of the CFRP-steel double-lap joint under constant temperature (20℃, 50℃) and seawater. It indicated that the longer the exposure time, the more significant the stiffness and strength degradation, especially in the early service stage. Similarly, Borrie et al. [123] found that immersing the CFRP-steel bond joint in water at 40 ℃ for four months significantly reduced the shear and tensile limit load-to-failure.

Dry/wet cycling caused microcracks in the adhesive layer of the CFRP-strengthening system, weakening the ability of the matrix to transmit stress. For example, the ultimate failure load of the I-beam retrofitted with CFRP was reduced by 4.3%, subjected to 32 dry/wet cycles later [124]. Similarly, Li et al. [116] found that the bond strength decreased by 30.7% after 360 dry/wet cycles under saline and room temperature conditions. However, Kim et al. [126] found that the failure load of the CFRP-steel double-lap joints was increased by 31.8% after 100 cycles under water and room temperature conditions. They thought the cohesive properties were enhanced due to additional curing of the adhesive caused by moisture. In addition, the CFRP retrofitted notch steel beams studied by Li et al. [125] demonstrated that the over-damage mainly occurred near the notch, which caused the penetration of salt solution and further reduced the bond performance of the adhesive. In conclusion, current investigations focused on experiments to reveal the effect of dry/wet cycling on the bond strength of CFRP-steel but lack studies on bond strength models and bond-slip relationships and with insufficient understanding of the failure mechanism. Therefore, more research is urgently needed to fill these gaps in the future.

3.5 Ultraviolet radiation

Ultraviolet (UV) radiation can cause aging of the CFRP-steel bond interface, leading to a change in the molecular structure of the adhesive and thus affecting its bond performance. Previous studies have shown that 6% of total solar radiation was UV radiation [102]. Literature [127] pointed out that the UV photons absorbed by polymers result in photooxidative reactions that alter the chemical structure, leading to material properties deterioration. When the CFRP was employed to strengthen steel structures outdoors, it was inevitably exposed to ultraviolet radiation. Therefore, the CFRP-strengthening system was studied by most researchers who focused on CFPR and adhesive materials [102]. Silva et al. [128] have shown that the pultruded rods based on CFRP were exposed 3000 hours later under UV; its modulus had decreased substantially, but the tensile strength was not affected. Similarly, the study by Nguyen et al. [129] demonstrated that it hardly influenced the tensile strength of CFRP, while the tensile strength and modulus of epoxy resin were increased by 13.9% and 105%, respectively. They have shown that the strength of the CFRP-strengthening system was decreased, but the stiffness increased when exposed to the UV. The phenomenon was caused by the temperature effect rather than the UV itself. Amorim et al. [24] found that the bond strength for the bond joints processed by surface sandblasted, sanded, and chemically cleaned increased by 145%, 306.8%, and 22.7% after UV radiation, respectively. This is because UV radiation activated the post-curing process of the adhesive and promoted the formation of a cross-linking network in the polymer, improving its mechanical properties. In conclusion, the trend of bond joint strength was closely related to the mechanical properties of epoxy adhesives, indicating that the type of adhesive has a specific influence on the bond performance of the CFRP-strengthening system. Therefore, the effect of UV radiation on the CFRP-strengthening system needs more investigation.

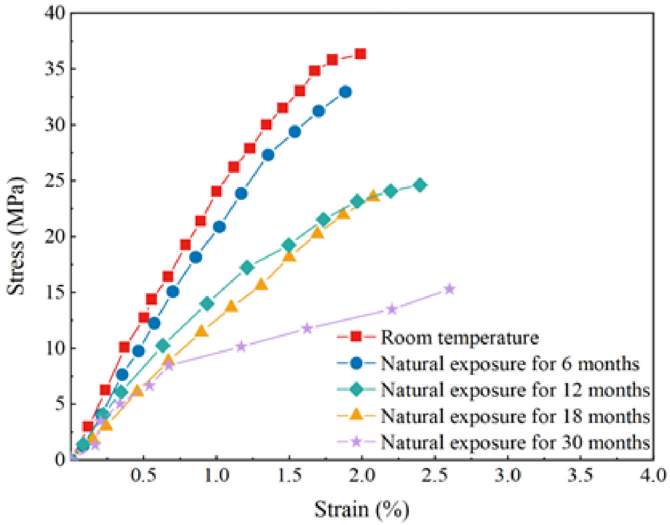


Fig. 16. Relationship between stress and strain of the epoxy adhesive matrix after various exposure times [113].

3.6 Freeze-thaw cycles

This study summarized the investigations on the effect of freeze-thaw cycles on the CFRP-strengthening system in recent years, as shown in **Table 2**. The elastic modulus and tensile strength of CFRP and adhesive were studied by literature [63,130,131] under multiple freeze-thaw cycles. The results show that the change in CFRP performance can be ignored under the freeze-thaw condition, but the elastic modulus and tensile strength of the adhesive were decreased significantly, resulting in the interfacial bond strength. Moreover, the failure mode of the CFRP-strengthening system was also affected by the freeze-thaw. For example, Agarwal et al. [25] showed that the interfacial bond strength decreased with the free-thaw cycles, and the failure mode changed from cohesive failure to a mix of cohesive and interface debonding failure [26].

Table 2. The effect of freeze-thaw cycles on bond behavior

Reference	Joints geometry	Adhesive types	Freeze conditions	Freeze-thaw cycles	Failure modes
Agarwal [25]	Single-lap	Sikadur-330	-18°C/16h ~ 38°C/8h	0 20 30 40	Cohesive failure
		Sikadur-30		0 20 30 40	CFRP delamination & adhesive failure
Pang [131]	Single-shear	Araldite-2015	-20°C~8°C 5-6h per cycle	0 50 100 200	CFRP delamination changed to cohesive failure
Pang [132]	Single-shear	Sikadur-30	-20°C~8°C 5-6h per cycle	0 50 100 200 300	CFRP delamination
Yang [130]	Double-strap	Sikadur-30	-20°C~20°C the change rate of 0.5°C/min repeatedly	0 83 208 292 417	HIT-CFRP: cohesive failure SIKA-CFRP: adhesive failure
Wang [133]	Wedge	Epoxy-LLC	-18°C/3.5h ~4°C/2h	0 50 100 150	CFRP delamination changed to adhesive failure
Heshmati [110]	Double-lap shear	Lim-567	-20°C/6h ~20°C/6h	0 25 125	Cohesive
Kim [126]	Double-lap shear	Epoxy adhesive	-20°C/6h ~23°C/16h	0 25 50 100	Adhesive failure

The freeze-thaw influenced the bond-slip behavior of the CFRP-strengthening system. Pang et al. [131] investigated the interface bond-slip relationship evolution of the Araldite 2015 adhesive CFRP-steel lap specimens. The results show that the interface strength increased slightly at the early stage of freeze-thaw cycles and then decreased with the increase of freeze-thaw cycles. The trapezoidal model characterized the bond-slip relationship. Furthermore, the ultimate load of the strengthening system was reduced under 200 freeze-thaw cycles when the adhesive was used to Sikadur-30, and the bond-slip relationship was characterized by a bilinear model [132]. The effect of freeze-thaw cycles on model I fracture behavior of the CFRP-strengthening system with numerical simulation methods demonstrated that the experiment agreed with the simulation, and the interfacial fracture energy decreased by 32.72% after 150 freeze-thaw cycles. The failure modes were CFRP delamination and adhesive failure, corresponding to the unfreezing and freeze-thawing [133]. The bond performance of the CFRP-strengthening system was subjected to negative impact under a freeze-thaw environment, and the weakness lay in the adhesive and bond interface. **Fig. 17** shows the relationship between normalized bond strength and the freeze-thaw cycles. The normalized bond strength was the ratio of the bond strength after freeze-thaw to the bond strength at room temperature. The results show that the bond strength of CFRP-steel lap joints made with traditional structural adhesives decreased with freeze-thaw cycle numbers. However, Yang et al. [130] found that the mechanical properties of HIT- and SIKA-CFRP-steel bond joints were less affected by the freeze-thaw cycle. This was mainly attributed to the fact that only the elastic region at the interface was activated during the thermal cycle, resulting in a lower impact of pure thermal cycling aging on CFRP-steel bond joints. In conclusion, there is limited research on the effect of the freeze-thaw cycle on CFRP-steel bond joints, and the aging mechanism is not yet clear. Therefore, further research is urgently needed to clarify the influence of freeze-thaw on the CFRP-steel bond behavior.

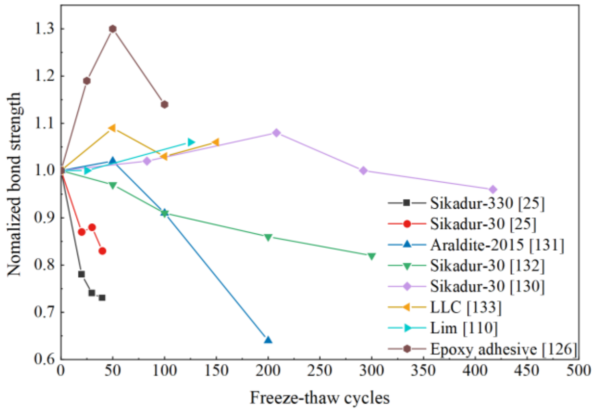


Fig. 17. The normalized bond strength vs. freeze-thaw cycles.

4 Remarks and prospective

For the FRP repair of steel structures, researchers have been dedicated to enhancing the stability, load-bearing capacity, fatigue behavior, and durability performance, with the ultimate aim of extending the service life of steel structures. This article reviews the recent research outcomes of the impact of key characteristics of the bonded joints, including the CFRP modulus, adhesive performance, bond length, adhesive layer thickness, and bond joint geometry, on bond performance of the CFRP strengthening systems. Additionally, the influences of environmental factors, including the elevated and sub-zero temperature, moisture, corrosion, humidity and wet-dry cycles, ultraviolet radiation, and freeze-thaw cycles on the bond behavior, were also reviewed. The review also offers specific research prospections for future research.

The use of nanomaterial modification and film adhesives could overcome the shortcomings of traditional epoxy resin adhesives, such as poor high-temperature ductile and low room-temperature bond strength. However, their practical engineering applications and widespread adoption are limited due to production costs and time constraints. These issues require further in-depth research and the development of solutions.

The influence of adhesive layer thickness on the bond performance of CFRP strengthening systems requires further research. Studies should be conducted to determine the optimal adhesive layer thickness to prevent the occurrence of the adhesive layer and interface failure.

Geometric modification or mechanical anchoring of the CFRP-steel bonded end is an effective method to prevent the debonding failure of CFRP.

Temperature and humidity are considered the most crucial influence factors. Adhesives are softened under high temperatures and humid conditions, reducing their glass transition temperature (T_g) and degrading the bonding performance of CFRP strengthening systems. It is recommended that the maximum exposure temperature of CFRP strengthening systems be below 15°C above the adhesive's T_g.

Corrosion, wet-dry cycles, UV radiation, and freeze-thaw cycles are the critical environmental factors affecting the durability of CFRP strengthening systems. Existing research has focused on the individual effects of environmental factors. However, bonded joints used in outdoor construction (such as bridges) are typically exposed to a variety of complex environments. Future research should focus on durability studies under coupled environmental conditions.

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CRediT authorship contribution statement

Lu Ke: Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Youlin Li**: Formal analysis, Investigation, Validation, Writing –original draft. **Chuanxi Li**: Project administration. **Zheng Chen**: Project administration. **Kaibao Ma**: Writing – review & editing. **Junjie Zeng:** Writing – review & editing.

Conflicts of 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.

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