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Durability of Fibre Reinforced Polymer under Aggressive Environment and Severe Loading: A Review

Nur Hajarul Falahi Abdul Halim[1], Sophia C. Alih[2*], Mohammadreza Vafaei[3]
Mahmoud Baniahmadi[4], Ali Fallah[5]

[1,4,5] Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.
[2] Faculty of Civil Engineering, Institute of Noise and Vibration, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.
[3] Faculty of Civil Engineering, Forensic Engineering Center, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.
**Corresponding Author*

[1]Orcid: 0000-0003-0527-7722, [2]0000-0001-5326-3670, [3]0000-0002-9988-1842, [4]0000-0002-7665-4276
[5]0000-0001-9493-5242

Abstract

Fibre reinforced polymer (FRP) is currently used in construction industry to enhance structural performance, especially retrofitted structures. FRP has the advantages over other retrofitting techniques due to their fast and less complex installation process as well as causing fewer disturbances to occupants. The durability and high resistance of FRP under aggressive environmental condition make it superior compared to conventional reinforcement bars especially when structures are exposed to higher risk of corrosion. Its high strength-to-weight ratios give advantages to the application of FRP for seismic retrofit since an increase in weight will lead to increase in seismic force. Although in general FRP has high resistant to chemical, corrosion, and extreme weather as well as having high strength, their performance is very much affected by the mechanical properties, fabrication methods, types of materials used, etc. Understanding this behavior provides a good insight into the superiority and benefits of FRP compared to other construction materials as well as their limitations. This paper reviews the durability of FRP under aggressive environment and severe loading. Provisions in design codes are also included to provide guidelines for the application of FRP under these conditions. It covers different types of FRP in laminates and bar form. A lot of research has been conducted to better understand the behavior and performance of FRP, however, studies on some aspects are still limited. This includes the performance of FRP under impact loading.

Keywords: Fibre Reinforced Polymer (FRP), Durability, Reinforced concrete structures, Aggressive Environment, Severe loading.

INTRODUCTION

The use of fibre reinforced polymer (FRP) composites to strengthen, rehabilitate and retrofit civil engineering structures have become popular in structural field due to their important advantages such as ease of application, minimum disturbance to the occupants and savings in construction cost and time in addition to their advanced mechanical properties RP composite materials are durable and have reasonable fatigue life. They have high strength-to-weight ratios and are easily adapted almost to any shape and size of structure [1-4]. FRP is corrosion-resistant and largely weather-resistant as well as having excellent chemical resistance [5]. Moreover, FRP composites are lightweight and relatively cheap to manufacture [6]. The mechanical properties of FRP composites are dependent upon the ratio of fiber and matrix material, the mechanical properties of the constituent materials, the fiber orientation in the matrix, and ultimately the processing and methods of fabrication [7, 8]. The application of FRP laminates is basically to upgrade the flexural capacity of structures, as well as increasing shear, tensile strength and load carrying capacity of structures [9-14]. Three different types of FRP have been used for strengthening of concrete elements that are called Carbon Fibre Reinforced Polymer (CFRP), Glass Fibre Reinforced Polymer (GFRP) and Aramid Fibre Reinforced Polymer (AFRP).

Due to extremely high demand of FRP applications in the construction industry, researchers are encouraged to extend investigation on the durability of FRP reinforcements, especially under different environmental conditions and loadings as these affect the bonding and performance of FRP. The durability of FRP jackets in civil construction has been reviewed by Boer *et. al.* and Sen [15, 16]. However, the existing information only focuses on the impact of the aggressive environment towards the bond behavior of FRP laminates or the wrap system.

This paper focuses on the impact of aggressive environment and severe loading on mechanical properties of both FRP laminates and bars. Hence, to critically understanding the durability of FRP under such conditions, both experimental and numerical studies are included in the discussion. In addition, recommendations from design codes to include factors from the environmental conditions are also discussed for guidelines in the application of FRP.

DURABILITY OF FRP UNDER AGGRESSIVE ENVIRONMENT

Thermal conditionings

Previous studies show that the FRP reinforcement is affected by elevated temperature (Table 1). Different types of FRP are used to investigate the mechanical behavior towards the elevated temperature [17-19]. For FRP bars, it is shown that GFRP and BFRP melted and totally lost their tensile strength at a temperature up to 450˚C. The tensile strength reduced from (45-55%) and (20-30%) respectively at a temperature of 325˚C. Even though CFRP bars exhibit a lower reduction of bond strength among the other types of FRP reinforcement, the steel bars are still the best to work with concrete with higher bond strength and stiffness under elevated temperature. The glass transition temperature of FRP adhesive system experienced changes of phase and markedly different material properties due to high temperature [20]. In addition, three different failure modes are found depending on the types of FRP laminates at elevated temperature; 1) brittle fiber ruptures at 100 to 150˚C, 2) softened of epoxy adhesive at 200 to 250˚C and 3) burned of adhesive and the specimens failed at 300˚C [18]. It has been stated that hybrid CFRP-GFRP laminates exhibit better fire resistance with lower reduction of elastic modulus which can maintain their tensile strength under elevated temperature compared with single-FRP laminate [18, 19, 21]. Thus, more studies are encouraged to investigate the behavior of RC members externally bonded using this method under elevated temperature.

On the other hand, different mechanical reactions of FRP were found at low temperatures. Yao *et. al.* [22] concluded that the average bond strength and shear stiffness of BFRP-steel single lap joints increase at a lower temperature from -25 to 50˚C and -25 to 25˚C, respectively. Nevertheless, under a lower temperature of -40˚C, the bond strength of FRP sheets is adversely affected as described in Table 1 [23], which means the bond strength of FRP laminates are affected under both conditions; low and high temperatures. This can happen to the FRP bar as well due to its different mechanical properties reaction below a temperature of 350˚C [24]. However, it is noticed that for a combination of temperature and mechanical response, low temperature may not severely affect the performance of FRP compared with elevated temperature.

Moreover, under elevated temperature, the application of epoxy resin as an effective adhesive layer between FRP laminates and concrete interface to enhance the bond strength and reduce flexural de-bonding failures was unsuccessful [25]. This is because, at the stage of 200-250˚C, the epoxy adhesive has started to soften and completely burned at a temperature of 300˚C. The numerical and analytical studies on the interfacial rupture of FRP-concrete [26, 27] with the assumptions of failure modes based on adhesion laws in the case of Fracture Modes I and II (Fig. 1) indicate that the initial bond strength between concrete and FRP influenced by the increase of effective bond strength at the early stage of elevated temperature. However, the predicted bond strength of the following remained as a theoretical concept, in which there is no further experimental study. Instead, using nanoclay as coating system suggested by Ji *et. al.* [28] may improve the fire resistance and bending strength of FRP jacketed RC beams than non-coating RC beams which can exceed maximum temperature of 990˚C. Since the application of nanoclay is effective to improve the fire resistance of FRP laminates, further study may be required to assess the validity of this coating system on FRP bars as they are also affected by elevated temperature. This is because the design protocols indicate that the FRP system with the protective coating may lessen the effect of reduction factor caused by the aggressive environment [29].

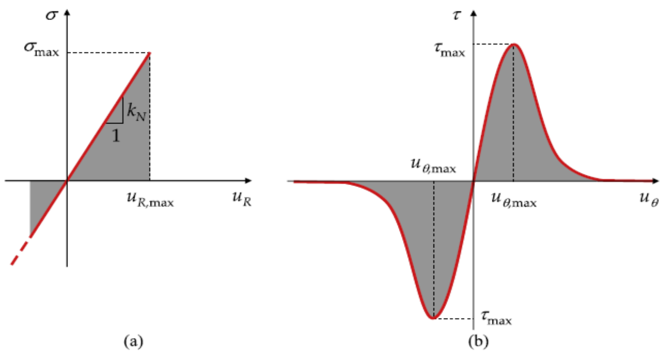


Figure 1: The adhesion law used to propose non-linear analytical model: (a) Mode 1; and (b) Mode II [26]

Furthermore, as we can see in Table 1, most of the studies are conducted using tensile loads to determine the mechanical properties of FRP bars and laminates. However, some types of FRP samples may not be able to be tested due to severely damaged at elevated temperature [17]. Somehow, under a compression load, GFRP composite exhibit better performance and higher residual strength than wood, concrete, and steel [30]. This is because, under thermal cycles conditions, the durability of GFRP does not significantly affected by the high temperature and able to restore 75% of their original load capacity after one hour of cooling down. By adopting this method, the mechanical response of FRP may be determined without undermining the specimens before performing the mechanical test. Hence, the test on different types of FRP specimens at different elevated temperature should be highlighted [31, 32].

Chemical Solutions

Table 2 presented different types of FRP subjected to a different chemical test. This is because the FRP composites tend to be sensitive to harsh environments [33]. Particularly, the alkaline solutions and saltwater result in decomposition that affects glass fibers in both bars and laminates form [34]. The interface of fiber and matrix degrade adversely in terms of fracture toughness. Although the FRP bars may have advantages as it does not corrode like steel bars, unfortunately, due to their hydrolysis characteristic, the mechanical properties, as well as bond behavior, are adversely affected.

Furthermore, the investigation on FRP systems under chemical solutions has been conducted simultaneously at elevated temperature. Chen *et. al.* [35] exposed CFRP and GFRP bars to five different solutions (Table 2) and accelerated the aging effect at elevated temperature to simulate the coupling effects as expected in real environments. The result showed that the exposure to solutions at 60˚C had adversely influenced the strength and bond behavior of both bare and embedded GFRP bars. However, it is recommended that the immersion in saltwater and alkaline solution at room temperature are more appropriate for environmental conditioning to assess the mechanical effect of FRP materials and the bond behavior [20].

Cromwell *et. al.* [20] conducted an experimental test on the environmental durability of FRP externally bonded RC beams. It is reported that pronounce degradation of the bond strength occurred due to the failure of an adhesive layer between the concrete-FRP. Thus, Quagliarini *et. al.* [36] have proposed the coating system using Polymethyl methacrylate (PMMA). It is reported that the application of the coating system on BFRP bars exhibits higher alkaline resistance through gravimetric measurements. Thus, this method can be used to enhance the alkalinity of GFRP bars. Moreover, a vinylester resin is recommended for FRP bars under chloride attack, while it also able to decrease the water leakage rate of FRP laminates [36]. Besides, two types of cement-based mortar, namely polymeric and self-compacted had also been studied and recommended for flexural members to increase the ultimate strength of the specimens as well as to exhibit higher bond strength [37]. The properties of adhesive after the accelerated aging test can be determined based on ASTM D4475 [38]. Meanwhile, acid treated fiber rope showed satisfactory durability even with a reduction of tensile strength [36]. This has surely confirmed that basalt fiber is not significantly affected by acid solutions. However, more studies on the mechanical properties of FRP laminates and its behavior on the real structures under environmental conditions are needed, since the FRP jacketing is widely used to retrofit RC structures.

On real corroded RC structures, the external surfaces of corroded RC structures may be deteriorated as well as degrade in flexural strength due to exposure to marine environment [39]. Thus, in designing the protective method as well as to avoid the repetition of corrosion effect on RC structures, parameters including the number of FRP layers and the diffusion barriers to prevent the leakage rate is considered [40]. A significant improvement performance of damaged RC columns retrofitted with FRP laminates is found along the increased number of FRP layers with adequate anchorage system. Studies on the behavior of corroded RC columns retrofitted with CFRP jacket has been proven that excellent increased strength, load-bearing capacity, and ductility of the specimens jacketed using CFRP sheets [41]. In addition, the FRP confinement impeded the corrosion rate after wrapping and the post-repair corrosion resulted in no loss of strength or stiffness with only slight reduction in the ductility of the confined specimen. In addition, CFRP jacket always showed better confinement on corroded RC structures due to their high mechanical properties rather than GFRP laminates [42].

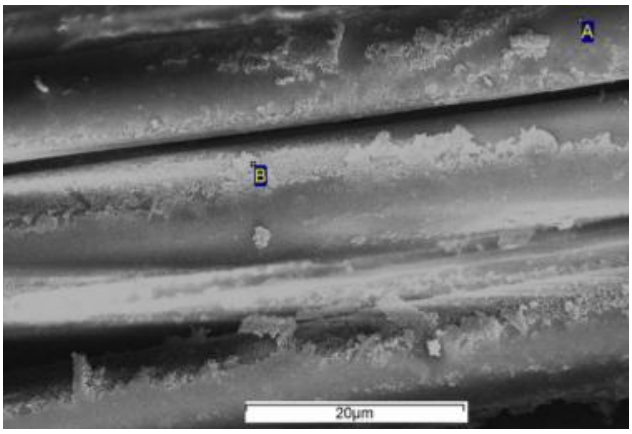
According to American Concrete Institute (ACI 440.2R-08) [43], the ultimate tensile strength of FRP laminates, f_{fu} and the effective strain, ε_{fd} to prevent immediate debonding failure can be determined as follows:

$$f_{fu} = C_E f_{fu^*} \qquad (1)$$

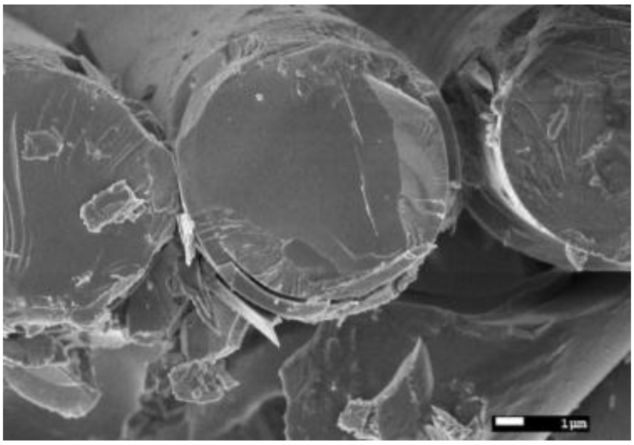
$$\varepsilon_{fd} = 0.41\sqrt{\frac{f'_c}{nE_f t_f}} \leq 0.9\varepsilon_{fu} \qquad \text{(SI units)} \qquad (2)$$

where C_E is the environmental factor; f_{fu^*} ultimate tensile strength of the FRP material as reported by the manufacturer; f'_c is specified compressive strength of concrete; number of plies of FRP reinforcement; tensile modulus of elasticity of FRP; and the nominal thickness of one ply of FRP reinforcement. From the equations above, the factor of C_E is only used for material properties while no exposure factor is considered to determine the bond strength of FRP laminates. Thus, based on Cromwell *et. al.* [20] findings, the environmental 'knockdown' factors are introduced for bond capacity, with expected material quality 0.90 for CFRP plate and 0.50 for CFRP fabric. The bond capacity factor of GFRP fabric is not yet proposed since it is rarely used in North America. Besides, externally bonded FRP also can be calculated in retrofitting metal structures (e.g. steel) using Italian design guidelines [29]. For FRP internally reinforced concrete structure, the strength reduction factors are provided through consideration of the effects of sustained stress, fatigue, and environmental conditions [44]. However, the estimate tensile strength is lower than the experimental results [45]. Other countries including Canada and Japan had also established the guidelines for FRP bars use in concrete reinforcement (i.e. CAN/CSA-S06-00 and JSCE).

In addition, in terms of the testing method in experimental work, most of the studies performed a tensile test to determine the mechanical properties of FRP materials (Table 2). However, fatigue loads should be included in the loading protocols, due to the observed fatigue effect on FRP bars under a real marine environment. In addition, rather than using data from experimental works, scanning electron microscopy (SEM) images as shown in Fig. 2 can be used to capture the degradation of fatigue strength of FRP material at different local temperatures [34, 46]. This method gives users and researchers more option in determining the properties of FRP under marine environment usage.



(a) Fracture surface



(b) Crack image

Figure 2: SEM images of corroded basalt fiber under alkaline environment [47]

Hygrothermal environment

The hygrothermal effect is a condition where heat and humidity movements occur in a building which can cause delamination of FRP laminates in jacketing structure members. Therefore, most of the studies conducted under hygrothermal are using FRP laminates or sheets as their experimental parameter (Table 3). Under hygrothermal environment, the FRP laminates with an adhesive layer are strongly affected during the wet-drying process due to water absorption as well as increased time and temperature [48, 49]. Longer periods of water-immersion tests exhibit better patterns at a downward trend in time, in which the stiffness and deflection changes are clearly detected [50, 51]. This clearly states that fatigue life of FRP sheets independently influenced by fiber configurations including type, volume fraction, and weaving, where fiber resistance is mainly influenced by interface failure.

Moreover, the methods of exposing the FRP samples can affect the conditioning process where severe deterioration may exaggerate the real situations [52]. For example, the interface exposed to air more than water is more related to thermal effects than the deterioration induced by moisture diffusion. As suggested by Amidi and Wang [53], half submission of FRP specimen in water (Fig. 3) may exhibit higher fracture strength than fully submission due to a better uniform distribution of the relative humidity along the interface.

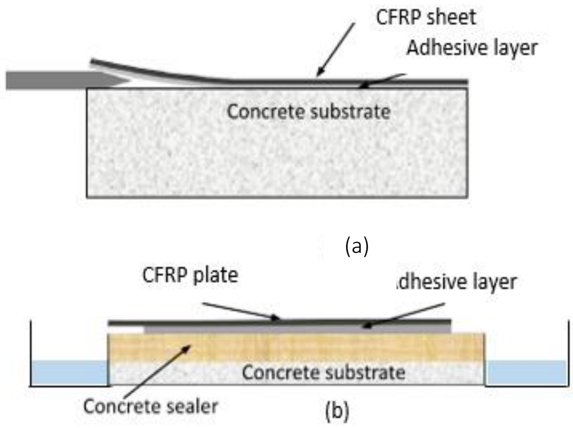


Figure 3: Method submission of samples (a) fully submission (b) half submission [53]

Furthermore, the selection of mechanical testing is important to determine the failure mode of the specimens after the hygrothermal environment. Based on the pull-out test, a common type of cohesive failure such as debonding of adhesive-cohesive is observed, similar to tensile load test [54, 55]. Nevertheless, by includes the fatigue loads after hygrothermal environment allow us to assess the influence and the stress level towards the fatigue damaged of FRP-concrete interface [56]. Thus, more studies are needed on the combined effect of accelerated aging and fatigue loading with more critical temperature-humidity relationships. In addition, a numerical modeling with the general method of hygro-thermo-mechanical analysis has been developed using differential equations formulated by Phillips and De Vries [57, 58] that demonstrated the effect of temperature gradient on the moisture distribution. This provides more guidance to assist with the design of FRP and building structure to reduce the interfacial pressure caused by moisture absorption and thermal expansion properties of constituent materials [15].

Besides, due to debonding of concrete material during the hygrothermal attack [56], Maljaee *et. al.* [55] have been proposed a physical treatment called grinded surface treatment to improve the surface of the concrete structure. The experimental work has been carried out on the masonry bricks and resulted in significant improvement of bond behavior compared with the bricks without surfaces treatment [59]. Meanwhile, to improve the bond failure between FRP-concrete that caused by adhesive layer, silane coupling agent is suggested [53]. However, optimum potential results are still needed as observations are made in limited circumstances. Additionally, more studies on FRP reinforced RC structure under hygrothermal environment should be carried out, due to the creep of concrete where the continuous loading has caused local degradation of bonds between bars and concrete at the crack mouth [60].

DYNAMIC LOAD

In civil constructions, building structures may as well expose to dynamic loads due to earthquake, terrorism, industrial explosion and vehicle accident. Because of the demand for FRP usage to retrofit and strengthen old and new buildings, the durability of FRP under dynamic loads are reviewed herein.

Seismic Load

As seen in Table 4, FRP wrapping is observed to have excellent seismic confinement as they improve the strength, ductility, load carrying capacity, failure mode and dissipation energy capacity of RC structures. This method has its own advantages compared to other retrofitting techniques like RC jacketing since it has least changes to the dimension of existing structural elements that need to be retrofitted and the procedures can be carried out with limited interruption to the serviceability of the buildings. FRP wrapping is suitable to be used to increase the capacity of RC columns in buildings with soft story phenomenon and a low-ductile structural element that may experience high inter-story drift when subjected to earthquake load [61].

However, the limitation of FRP internal reinforcement in seismic retrofit is the rupture of FRP reinforcement under severe level of earthquake loads. When subjected to high intensity earthquake, FRP might experience brittle failure similar with unconfined RC columns due to rapid reduces of load-carrying capacity after the yield of longitudinal steel bars. From the observation, RC columns with fully wrapped of FRP sheets tend to create a failure at hinge region due to early yielded of longitudinal reinforcements [62]. Hence, based on Wang *et. al.* [63], FRP jacketing in the potential plastic hinge areas with the height of confined area 1.1 times larger (pre-damaged columns may need larger) than the cross-section diameter can improve the behavior of circular RC columns. The confinement method using rectangular or square columns indicates different result as the shapes of the column is considered as testing parameters. Perera [64] developed a numerical analysis on seismic retrofit of circular and rectangular columns using advanced composite jacketing due to insufficient internal transverse confinement at the flexural plastic hinge area during the experimental works. A simplified damage model based on continuum damage mechanics has been developed for seismic assessment and capable to predict the ultimate ductility and load-bearing capacity of the confined structure under seismic load. Similar loading protocol on FRP jacketing masonry structure has been studied [65]. However, lower frequencies of ground motion caused the buildings experience not enough acceleration [66].

Moreover, Table 4 shows limited research is notable on the preloaded or pre-damaged effect on FRP strengthened RC structure. This parameter is important due to more confinement will be needed compared with structures without damaged history. Nevertheless, the combination of BFRP laminates and BFRP bars generate big impact for seismic retrofit as they achieved the requirements of temporary repair and extend the emergency use of RC columns after the earthquake attacked [67]. Another confining method using a combination of FRP with other conventional materials (e.g. steel) has also been studied [68-71]. Those studies clearly state that the hybrid FRP materials could restore the strength of RC columns as well as pre-damaged RC columns. Hence, a future investigation is needed to ensure a better understanding of variables for seismic retrofit (i.e. different level of axial load, shear spans, damaged history and different cross-sections, as well as different types of FRP reinforcement).

In addition, FRP configurations play important role in testing parameters as they influence the behavior of confined RC members. For example, columns confined to least number of FRP strips exhibit less dissipation of energy [50]. However, the multi-layers of FRP sheets will reduce the ductility of confined concrete members compared with a single layer and low elasticity of FRP composites [72]. Design guidelines of FRP confinement using FRP bars and FRP laminates have been listed by Hollaway [73] in the review of present and future utilization of FRP composites in civil construction. Whereas, Japan has established a guideline for upgrading works of the concrete structure using FRP jacketing [74]. The guideline includes the design method for seismic attack preparation as well as restoring earthquake-damaged of concrete structures.

Table 1: An overview of previous research covering the types of FRP specimens under elevated or very low temperatures with different variables and testing method.

Researcher(s)	Types of specimens	Types of conditioning	Variables	Method of testing	Findings
Yao *et. al.* [22]	BFRP/Steel single-lap joints	Elevated temperature	Temperature and loading rate	Dynamic tensile test	The bond behaviour between BFRP and steel joints started to degrade as low as 50˚C to 100˚C
Hamad *et. al.* [17]	BFRP, GFRP, CFRP and steel bars embedded in concrete	Elevated temperature	Temperature and types of bars	Pull out test, compression and tensile tests	The FRP-concrete started to debond and lost about 81.5% of their bond strength at 325˚C. Meanwhile, the GFRP and BFRP bars experienced severe degradation on their mechanical properties and melted at the elevated temperature of 450 ˚C.
Wang *et. al.* [24]	CFRP and GFRP bars embedded in concrete	Elevated temperature	Types of FRP bars and temperature	Tensile test	FRP bars are critically affected at the elevated temperature of 350˚C. FRP bars retain a very high level (90%) of their original stiffness below that temperature.
Hawileh *et. al.* [18]	CFRP, GFRP and hybrid CFRP-GFRP laminates	Elevated temperature	Types of FRP and temperature	Tensile test	The initial brittle failure occurred at the elevated temperature of 100˚C to 150˚C. Hybrid FRP laminates showed better performance with a small reduction of elastic modulus up to 250˚C.
Ghadimi *et. al*. [30]	Pultruded GFRP	Thermal cycles	The number of cooling-heating cycles and temperature	Compression test	The GFRP shows semi-plastic behaviour before final collapse, where significant deformation is observed.
Shi *et. al*. [19]	BFRP, CFRP, GFRP and hybrid CFRP-BFRP sheets	Freeze-thaw cycling with sustained loading	Types of FRP and the number of freeze-thaw cycles	Tensile test	A significant effect of freeze and thaw cycling occurred on CFRP and GFRP sheets. The hybrid specimens enhance the durability as well as the tensile behavior of FRP sheets under freeze-thaw conditions. Sustained loading does contribute to the degradation of tensile strength and rupture elongation of FRP sheets.
Ferrier *et. al.* [23]	CFRP sheets	Low and elevated temperature	Temperature and FRP-strengthening system	Tensile test	The low temperatures significantly affect the bond behavior of FRP sheets, but no influenced of decreasing the ultimate strength of the lap joint.

Table 2: An overview of previous researchers related to the reaction of different types of FRP in chemical solutions with different variables and testing method.

Researcher(s)	Types of specimens	Types of conditioning	Variables	Method of Testing	Findings
Micelli and Nanni [75]	GFRP and CFRP bars	Alkaline solutions	Types of FRP bars and exposure durations	Tensile test	Inadequate polyester resin protection badly affects the durability of FRP reinforcement, especially GFRP bars.
Quagliarini *et. al*. [36]	Basalt fibre ropes and BFRP bars	Water, acid and alkaline solutions	Chemical solutions and coating system	Tensile test	The uncoating specimens are sensitive to alkaline attack. Polymethyl methacrylate (PMMA) coating system improve the alkalinity of BFRP bars.

Y. Chen *et. al.* [35]	CFRP and GFRP bars	Water, alkaline solutions, saline solution, and combined alkaline solution with chloride-ions at elevated temperature	Types of FRP bar, types of conditioning, concrete type, temperature and exposure durations.	Tensile test and pull out test	The constituents of fiber effects the durability of FRP bars. Better alkaline protector of FRP bars is encouraging.
Silva *et. al.* [34]	GFRP laminates	Salt fog cycles and salt water immersion	Exposure durations and temperature	Tensile test	GFRP laminates reduced its tensile strength in saltwater immersion.
Shi *et. al.* [76]	BFRP bars	Salt water immersion at elevated temperature	Temperature and exposure durations	Tensile and fatigue tests	Scanning electron microscopy (SEM) images revealed the fatigue strength degradation on FRP bars.
Cromwell *et. al.* [20]	i) CFRP and GFRP sheets, CFRP plates ii) FRP externally bonded RC beams	Water, salt water, alkaline, elevated temperature, diesel fuel exposure	Types of conditioning, types of FRP specimens and exposure durations	Tensile test, short beam shear test and flexure test	The initial damaging effect the whole performance of CFRP and GFRP laminates especially the bond strength. Salt immersion and alkaline environments significantly effect GFRP specimens.

Table 3: An overview of previous studies on hygrothermal behavior of FRP.

Researcher (s)	Types of specimens	Types of conditioning	Variables	Method of Testing	Findings
Nakada and Miyano [49]	CFRP and GFRP laminates	Hygrothermal conditions	Temperature, types of FRP and resin, and types of loading protocols.	Three-point bending fatigue tests	Using time-temperature superposition principle (TTSP) master curves to predict the fatigue life of FRP laminates.
Zheng *et. al.* [56]	CFRP laminates	Hygrothermal conditions	Types of fatigue loads	Static and fatigue tests	The bond strength and fatigue of CFRP-concrete remarkably affected by the hygrothermal condition.
Amidi and Wang [53]	CFRP laminates and CFRP plate	Hygrothermal conditions	Distribution of moisture, types of adhesive	Water absorption test	Half immersion conditions produced more uniform distribution along the interface compared to conventional immersion. Silane coupling agent can enhance the bond strength between FRP-concrete under moisture distribution.
Korta *et. al.* [54]	CFRP composite, aluminium and steel	Hygrothermal conditions	Properties of sample, humidity-temperature cycles	Shear and tensile tests	Most of the samples failure under mechanical test. Application of epoxy adhesive is recommended under harsh environment.
Ghiassi *et. al.* [50]	GFRP composite	Moisture effects	Immersion period	Pull out test and single-lap shear test	The reduction of both tensile and compression strengths determined in water immersion.
Grammatikos *et. al.* [77]	Pultuded GFRP sheets	Hygrothermal conditions	Temperature	Moisture absorption, tensile test, dynamic mechanical thermal analysis, SEM, Fourier transform infrared spectroscopy and Computed Tomography	Elevated temperature accelerates the absorption of moisture rate and moisture diffusion coefficient. No effect on tensile strength and elastic modulus of specimens, except for aging at 80˚C.
Fergani *et. al.* [60]	GFRP and BFRP reinforced concrete beams	Hygrothermal conditions	Conditioning and sustained loading	Sustained loads test	Larger deflections occur in water condition. Sustained load cause increased of crack spacing due to a reduction in bond strength.
Maljaee *et. al.* [55]	GFRP externally bonded masonry bricks	Hygrothermal conditions	Surface treatment	Pull out test and single-lap shear test	Bricks with grinding surface treatment improve the bond behavior.

Table 4: An overview of existing studies on seismic behaviour of FRP strengthened structures

Researcher (s)	Confining materials	Types of specimen	Variables	Loading protocol	Findings
Mooty *et. al.* [72]	CFRP and GFRP sheets	Half scale square and rectangular RC columns	Shape of column, thickness and types of FRP sheets, cross-section and technique of jacketing, load protocol	i) Axial load ii) Lateral cyclic with constant axial load	FRP wrapped square columns shows better performance than in rectangular columns. No big effect on the performance of square columns when increasing the aspect ratio in wrapping method. CFRP increase the ultimate load of columns better than GFRP confinement.
Wang *et. al*. [78]	CFRP laminates	Full scale circular RC columns	Dimension of column, internal hoop steel reinforcement, layers of CFRP laminate and load protocol	i) Monotonic load ii) Cyclic compression loading	CFRP laminates increase both in axial stress capacity and axial strain capacity of the columns. The internal steel reinforcement influenced the performance of columns. The columns with the same dimension showed almost similar stress-strain curves for both cyclic and monotonic loads.
Sadone *et. al.* [79]	CFRP laminates and CFRP plates	Full scale of rectangular RC columns	Configurations of FRP	Constant axial load and lateral reverse cyclic load	Failure concentrated in the plastic hinge area. The extensive investigation on RC columns externally bonded with FRP should be done with the concern of anchorage system and confinement in plastic hinge zone.
Delgado *et. al.* [80]	CFRP sheets	¼ scale of square RC hollow piers	Details of transverse reinforcement	Cyclic load	The shear design of FRP retrofitted RC hollow piers enhanced the ductility of specimens. Retrofitted and original specimens showed similar energy dissipation, which significantly increases for higher top displacement.
Ouyang *et. al.* [81]	BFRP and CFRP laminates	2/3 scale of square RC columns	Numbers of FRP layer and types of FRP laminate	Lateral cyclic loads with constant axial load	The FRP sheets significantly improved the ductility of RC columns from brittle failure, energy dissipation, damping behavior under cyclic loads. The BFRP laminates able to replace the conventional CFRP laminates for seismic retrofit RC columns.
Colomb *et. al.* [62]	CFRP sheets and CFRP strips	Square RC short columns	Thickness of FRP laminate, numbers of FRP layer and their configuration	Lateral cyclic loads with constant axial load	FRP fully wrapped RC columns enhanced the failure mode from brittle to ductile failure. Columns with CFRP strips provide better dissipative behavior compared with fully wrapped columns. The thickness of FRP advantages for reinforced short RC columns where the central part is less likely to be embedded section.
Jiang *et. al*. [67]	Combination BFRP bars and BFRP sheets	Circular bride columns	Damaged history, retrofit method	Lateral cyclic loads with constant axial load	The proposed method achieved enhancing the flexural strength, displacement capacity and stiffness of columns. The BFRP sheets effective in preventing split concrete, buckling failure of NSM BFRP bars as well as improve the ductility of columns.

Blast Load

Blast load is an explosion which can cause catastrophic damage to the structural systems such as buildings, bridges, pipelines and industrial plants dams. Dynamic response of the structure to blast loading is complex to analyze, because of the non-linear behavior of the material. Therefore, a few parameters need to be considered before conducting the test, which includes charge mass and standoff distance, structure size, and orientation, the proximity of the target to other structures or to significant land features [68]. Table 5 shows previous studies on FRP confined structures under blast loading.

Table 5: An overview of existing studies on FRP confined structures under blast loading.

Researcher (s)	Confining materials	Types of specimen	Variables	Findings
Razaqpur *et. al*. [82]	GFRP laminates	RC slabs/panels	Explosion charge size	To identify the correct charge size and standoff distance, different test with different distances scales on more testing specimens are needed. The higher charge affecting the bond behavior of GFRP laminates.
Elsanadedy *et. al.* [83]	CFRP sheets	Circular RC columns	Stand-off distance, charge weight and damage level of RC columns.	The stand-off distance plays a very important role to resist the blast impact. The column decreased exponentially with the increase in the stand-off distance.
Aoude *et. al.* [84]	Ultra-high performance fiber	RC columns	Concrete type, fiber content, fiber properties, transverse reinforcement spacing and longitudinal reinforcement ratio	Types of concrete, fiber content, fiber properties influence the ability of structures to sustain larger blast loads before failure.
Wu *et. al.* [85]	Ultra-high performance fiber and pultruded CFRP plates	RC slabs	Types of concrete and externally bonded FRP	UHPFC is a more effective material for blast design than normal reinforced concrete (NCR).

Under blast loads, the standoff distance indicates different levels of damage on tested structures. For unconfined reinforced concrete column, the impact of close-in explosion shows spall concrete limited to a local area and is less sensitive to the column stiffness and boundary conditions [86]. However, the blast loads standoff distance and different charge of weight contribute different levels damaged by the structure need numerous experimental works, which is impossible to demonstrate on the real test. Therefore, the extensive study through finite element analysis is conducted [83]. As expected, the stand-off distance plays a very important role to resist the blast impact. The column decreased exponentially with the increase in the stand-off distance while the resistance of columns towards the explosion blast could be improved by increasing the number of FRP layers. Besides, through an analysis done by Lee and Shin [87], a reliable impact response is observed, which allow predicting both low and high levels of velocity impact towards the FRP confined masonry walls.

Furthermore, to improve the material used for blast load test, ultra-high fiber reinforced concrete members is suggested [84, 85]. It is concluded that the configuration of fibers and seismic reinforcement design are important in resisting blast attack on concrete structures. Moreover, the new inner core configurations of FRP sandwich panels (Fig. 4) under blast loads are formed by combining of woven and honeycomb shaped filled with sands [88]. The numerical analysis has shown good agreement with experimental measurements where the proposed method has significantly enhanced the performance of the panels under blast effects in terms of energy dissipation and deformation.

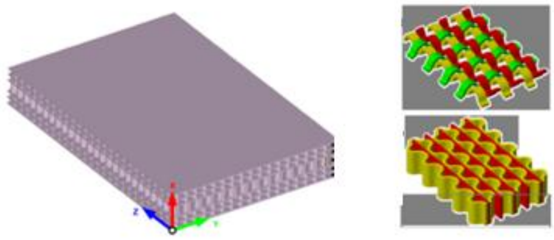


Figure 4: Example of FRP sandwich panels [88]

Impact Load

Impact loading is one of the external load which could affect the dynamic behavior of structures. The impact stress may occur due to the weight falling on the design object or perhaps from the design object that falls and pulls the hard surface. The mechanical properties of FRP composites under impact loading can be seen in Table 6.

Table 6: The mechanical properties of FRP composites under impact load

Researcher (s)	Types of FRP	Variables	Method of testing
Li *et. al.* [89]	Pultruded GFRP	Rate of impact load	Drop-weight tower with low-velocity impacts (free-falling carriage)
Sikarwar *et. al.* [90]	GFRP-epoxy laminates	Different fiber orientations and thicknesses	Gas gun impact
Caminero *et. al*. [91]	CFRP-epoxy laminates	Laminate thickness, Lay-up configuration	Drop-weight tower with low-velocity impacts

Based on Table 6, the variables tested including levels of impact energy and configurations of fiber are considered in FRP confined concrete structures as illustrated in Table 7. This shows that those variables play a significant role in influence the performance and failure mode of tested specimens [92]. The increase of impact load contributes to more extensive of delamination and higher values of peak deformation and energy absorption [91]. For GFRP composites, multiple shear damage modes occur at a high concentration of impact load. In addition, the low-velocity impacts produced extensive sub-surface delamination, where the dominant stress conditions caused failure in the level of fiber constitutive.

The main failure occurred under impact loading are delamination and ply cracking (due to thickness shear) and fiber fracture which related to properties of fiber [91]. The higher the thickness of FRP laminates with higher bending stiffness, will exhibit severe interlaminar stress and more extensive delamination in the external plies [89]. Instead, the absorption of energy, peak deformation, and duration of impact contact force decreased as soon as increased in thickness. However, the lower bending stiffness of thinner laminates will cause higher failure depth with permanent damage.

Table 7: An overview of existing studies on FRP confined structures under impact loading.

Researcher (s)	Confining materials	Types of specimen	Variables	Findings
Qasrawi *et. al.* [93]	GFRP tubes	Concrete Filled FRP tubes	Types of reinforcement, kinetic energy	The GFRP tube enhanced the flexural capacity and energy absorption compared to control specimens.
Huang *et. al*. [94]	GFRP tubes and steel spiral reinforcement	Circular concrete columns	Levels of impact load and strain rate, GFRP tube thickness and volumetric ratio of spiral reinforcement	The additional volumetric of spiral reinforcement improved the durability in GFRP confined under impact load.
Wang and Chouw [92]	Flax fiber reinforced polymer (FFRP) laminates	Coconut fibre reinforced concrete (CFRC) beams	Levels of impact load and FFRP laminate thickness	The deflection development of FFRP-CFRC specimens influence by a high degree of the damage levels and loading rate. The thickness of FFRP laminates influenced both the toughness and failure mode of confined CFRC beams.
Tabatabaei *et. al.* [95]	Long carbon fiber	Concrete panels	Types of long carbon fibers	Different types of fiber configuration showed different residual impact strength ratio and response on toughness in flexural tests.

Moreover, in terms of the application of FRP confined concrete under impact load, there are extremely limited studies are found. However, based on Qasrawi *et. al.* [93] and Huang *et. al.* [94], GFRP tubes are effective in protecting the concrete core and prevent it from spalling and crushing during impact tests. In addition, the additional steel reinforcement may help to improve the stress of GFRP tubes. For design purposed, the impact behavior of FRP laminates strengthening RC members is not yet been proposed in the design guidelines [29, 43]. Nevertheless, AFRP laminates are suggested as strengthening method due to its impact resistance rather than CFRP and GFRP [29, 96].

CONCLUSIONS AND RECOMMENDATIONS

This study presented a review on the durability of FRP under aggressive environment and severe loading based on previous researchers. According to the reviews that have been made, the following conclusions are drawn:

a) The performance of FRP with adhesive layer severely affected under aggressive environments. At elevated temperature, the FRP bars melted and totally lost their tensile strength at temperature up to 450˚C. Whereas, delamination or bond failure between FRP-concrete occurs in the presence of moisture and alkaline solution due to water absorption and corroded effect. Therefore, new coating system using nanoclay is suggested for elevated temperature resistance, and Polymethyl methacrylate (PMMA) for alkaline environment. For FRP-concrete exposure to the acid environment, a vinylester resin can be used as adhesive composites, instead, more research is needed for the use of silane coupling agent in the hygrothermal environment. Besides, grinded surface treatment is recommended to enhance the structure surface before the jacketing process.

b) Methods used in conditioning during laboratory test need to be taken into consideration to avoid exaggerating the real environment. For hygrothermal effect, half submission of FRP specimen in water is suggested which can exhibit better fracture strength than fully submission. Moreover, under elevated temperature, compressive test instead of tensile stress is suggested as testing method due to the extremely severe response of FRP bars at a temperature of 450˚C. This emphasizes that the selection of mechanical tests is important in determining the failure mode of the test specimen.

c) Furthermore, under severe loads, there are plenty experimental works have been done on seismic behaviour of confined structure using different types of FRP composite. Nevertheless, it is suggested to have an extensive study on the application of hybrid FRP under seismic loads. Additionally, as we can see, the awareness of the impact and explosion force against FRP-concrete structures is still lacking with limited studies conducted.

d) Additional design guidelines for FRP bars and laminates under aggressive environments are given in this study. However, guidelines for impact and explosive force have not been proposed yet. It should be noted by researchers to provide coefficient factors for impact and explosion force as there are many related cases such as violence and chemical explosions that affect structural performances.

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