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Review

State-of-the-art of prefabricated FRP composite jackets for structural repair

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A B S T R A C T

Fibre reinforced polymer (FRP) composites have attracted significant attention in repairing existing and deteriorating structures since the traditional rehabilitation techniques have several limitations in terms of durability, self-weight and complex installation process. Prefabricated FRP composite jackets are the preferred solution in repairing bridge piles located both underwater and above the waterline as they can be easily placed around the damaged pile to form a robust single-piece repair system. The structural continuity of the jacket in such a repair system is critical for effectively utilising its maximum strength. This study presents an extensive review of the current practices and new opportunities for using prefabricated composite jackets for structural repair. Important design considerations to effectively utilise prefabricated FRP composite jackets in repairing structures are presented and analysed. The review also identifies the challenges and highlights the future directions of research to increase the acceptance and use of emerging composite repair systems.

Contents

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1. Introduction

Across the globe, civil infrastructure, including highway bridges, roads, railways, ports, and airports is critical for economic development and progress. However, keeping this infrastructure in an efficient working condition is costly and challenging. Steel, timber and concrete structures are vulnerable to harsh weathering attacks including chloride and sulphate penetration, especially in marine or mining environments, that affect their integrity and cause their performance to deteriorate significantly [1,2]. For example, many coastal bridges experience corrosion after only 30 years of service, which is early, considering that they are designed for a service life of about 100 years [3]. A report on the durability of concrete structures cited in Nkurunziza et al. [4] stated that the cost of repairs and restoration constitutes a high percentage of infrastructure expenditure in many countries including Australia, the USA, Canada, and European Union countries. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) reported that corrosion damage costs the Australian economy more than $13 billion per year [5]. In the USA, around 40% of the 575,000 country's bridges are structurally and/or functionally defective due to steel corrosion [4]. The same problem exists in Canada wherein it is estimated that more than 40% of bridges constructed 40-years ago are suffering from significant steel corrosion [4]. Jumaat et al. [6] indicated that investments in maintenance and repair works on existing buildings represent about 50% of the total expenditure in construction. In most applications, repairing the damaged structures is preferable and more economical than replacing them due to the high cost of the new design, material, machinery and labour, plus the long extended service life of the effectively repaired structure. Hence, many industries and research agency are trying to optimise the current repair techniques and develop more effective ones. The Scopus database search conducted using the keyword "structural repair" was limited to engineering as a subject area and to article as a source type. It showed that the number of studies conducted on structural repair has been significantly increased from 2003 to 2018 (Fig. 1), highlighting the demand and necessity for an effective repair technique.

Rehabilitation of damaged and deteriorating structures with jackets made of concrete, steel, fibre-reinforced polymer (FRP) composites is now common and has been widely adopted as these jackets have high economic benefits by minimising the time the structure is off-service. Use of these jackets also results in significant savings in the amount of time and resources by decreasing the delay in daily operational services to a considerable level. Concrete jackets are used to retrofit damaged reinforced concrete (RC) structures with steel corrosion damage and concrete spalling. Many studies have shown that RC jackets can effectively restore the structural functionality of these deteriorated members [7–10]. In addition, steel jackets are also used to strengthen and retrofit RC members with structural defects [11–14]. The versatility of FRP composite materials has rendered them essential in civil applications [15–17], especially for strengthening and rehabilitation of civil infrastructure [18]. Many glass-FRP (GFRP) repair systems have already been used globally for rehabilitating damaged concrete, steel and timber structures and extending their service lives [19–24]. Similarly, Carbon-FRP (CFRP) is also good alternative to be used in seismic repairs and/or when more confinement pressure is required to achieve enhanced structural capacities due to their higher mechanical properties compared to GFRP jackets [25–33]. The availability of this wide range of composite jacket repair systems necessitates a targeted approach to evaluate the advantages and disadvantages of each technique in order to fully explore their potential in repairing damaged and deteriorating structures.

This study presents a systematic review of current practices for the repair of structures using prefabricated composite jackets and discusses the factors affecting structural repair using these jackets. The information on recent developments in prefabricated composite jackets for repairing structures helps to understand their performance and identify the critical factors in their application. Also, the paper identifies the gap in the state-of-art repair systems, and makes recommendations for new areas of research and development that need further exploration to increase the acceptance and use of emerging and new composite repair systems.

2. Current jacket repair systems

Splicing deteriorating steel and timber structures involves replacing the damaged part with a new section of the same material. For instance, a common practice for repairing corroded steel structures is bolting or welding a new steel section onto them

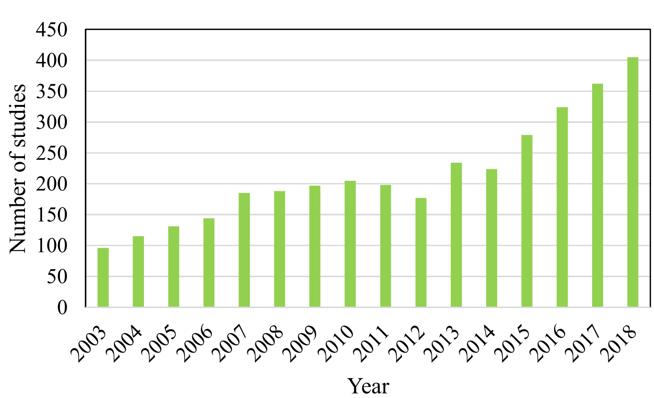


Fig. 1. Demand increase on structural repairs from 2003 to 2018 based on Scopus.

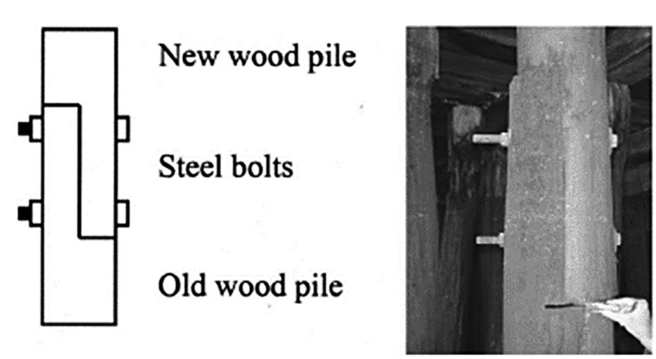


Fig. 2. Splicing of timber piles [21].

Fig. 3. RC columns repair using RC and steel jackets. a) RC jacket [8] b) steel jacket [14].

[34]. This technique was used for the first time in France in 1943, when rectangular steel bars were welded between a row of rivets to strengthen an old steel bridge [35]. Similarly, splicing timber structures involves removing the damaged portion of an old pile and splicing a new piece using metallic bolts, as depicted in Fig. 2 [21]. An example of this technique is the Kaase timber bridges repair in Ghana where 25 year-old decayed wood piles were replaced with new members made of the same type of original timber that the bridge was built with [36].

Fig. 3 shows RC and steel jackets in actual practice. Concrete jacketing is one of the earliest and most popular rehabilitation techniques for poorly detailed or deficient concrete and steel structures. RC jacketing/encasement has been utilised as a repair method for corroded steel and damaged wooden piles suffering from significant section loss [37]. Hawkswood [37] listed several cases of corroded steel piles successfully repaired using RC jackets including the14 tubular steel piles (610 mm diameter) used in Cork, Ireland and the 84H steel piles used on a fishing jetty in Lunenburg, Canada. For repairing the damaged structure, steel angle reinforcement was welded at the required location prior to concrete encasement. On the other hand, steel jackets normally consist of steel angles or plates and batten with different thickness, width and spacing [38] have been mostly used for strengthening square or rectangular sections. They are relatively easier to install, and have smaller thickness in comparison with the RC jackets. Cement or epoxy mortar fills the gap between the jacket and column. Several studies have been conducted investigating the effectiveness of steel jackets for repairing and strengthening RC structures [39–43]. Abdel-Hay and Fawzy [14] repaired the damaged RC columns with steel jackets wherein the corrosion was simulated by eliminating the stirrups in the middle third of RC columns. The jacket was anchored to the column using 10 pieces of 6 mm diameter anchor bolts on each side and an injection plaster was used to fill the gap between the steel jacket and the retrofitted column. The results showed that the repaired columns failed by concrete crushing outside the strengthened part at load of at least 90% of the ultimate load of the original columns.

Repairing the damaged and old structures using traditional materials like timber, concrete and steel is effective to some extent, especially in the short term. However, the repair approaches are interrelated with various aspects such as material compatibility, load transfer, connections, effectiveness, future maintenance, repair-downtime and environmental conditions, among other factors. As an example, the effectiveness of splicing damaged wooden piles is compromised due to the improper bearing vertical load transfer because of the gap in the splice between the surfaces of the two wooden pile portions [21]. Moreover, marine borers and shipworms enter through these gaps and attack the untreated wood. RC and steel jackets, on the other hand, are heavy and bulky, which enlarge the retrofitted members' size and reduce the free space of the structure. They also significantly increase the overall structural self-weight that affects the foundation and/or attracts more loads in seismic events [44]. Moreover, the anchorage of steel reinforcement for RC and steel jackets is a complex task. In the case of offshore structures, the production of the facility needs to be shut down during the so called "hot works" for safety reasons which significantly increases the total cost of welding repairs. In addition, steel jackets are not suitable for concrete structures in corrosive environments such as marine environments or a bridge subjected to de-icing salts [13]. Furthermore, repairing deteriorating structures using the same type of material that they were originally built with is impractical and ineffective in the long term because the repaired part will be subjected to the same condition that caused the deterioration to the original structure and the repair cycles may never end. More durable and reliable repair systems and materials with long-term effectiveness such as FRP composites are therefore warranted.

3. Prefabricated FRP composites repair systems

FRP composites offer unique benefits over conventional materials for strengthening and rehabilitation of civil infrastructure. In addition to their corrosion resistance characteristics, which is their primary feature, the ease of installation of the FRP composites makes them highly effective in addressing the drawbacks of conventional materials and repair practices like aggressive marine environments, limited access, self-weight and complexity of RC and steel jackets [45]. The availability in various forms including flexible thin sheets that can be wrapped around beams and columns is a remarkable advantage over rigid steel plates. Moreover, the superior properties of the FRP composites like lightweight, high strength, high fatigue capacity particularly for carbon-FRP, high impact strength, and durability [46], favoured it over the traditional repair techniques and qualified it for effective rehabilitating and strengthening applications to damaged RC and steel structures [47–49]. In addition to the strength requirements, FRP composites can also serve as a protective shield for the structural members against harsh environmental and weathering conditions such as chloride ions penetration, marine borers and waves which can rapidly cause concrete to weaken and deteriorate [21]. These favourable properties of FRP composites led to their gaining worldwide acceptance and significant attention from both researchers and construction industries. FRP composites have been effectively utilised in restoring the structural strength of damaged wooden piers in marine wharves [21], rehabilitating steel bridges [23], retrofit of corroded and severely cracked RC bridge bents [31], seismic repair of bridge columns with severe concrete crushing, and longitudinal steel bars fracture and buckling [25,26], rehabilitation of severely damaged precast RC columns connected with grouted splice sleeves and epoxy-anchored headed steel bars [50] and enhancing the strength and ductility of RC structures [51–56]. Based on their manufacturing method, FRP repair/strengthening systems are classified into two groups: wet lay-up and prefabricated systems [57].

Many researchers have successfully demonstrated the effectiveness of external wet lay-up FRP wrapping in repairing and strengthening RC structures [58–62]. In a study conducted by Sen and Mullins [19] pre-impregnated wet lay-up FRP repair systems were used for emergency repair of underwater circular RC piles in Tampa Bay, Florida, USA. The access to the piles in the deep waters was provided by divers for single isolated piles, and a custom-designed, lightweight modular scaffolding system was assembled around the piles in the same bent. The evaluation conducted by the authors two years after the wrapping indicated that the repair was successful and can be adopted in future projects. Manalo et al. [49] showed that a prepeg CFRP system can effectively restore the original stiffness and load carrying capacity of I-shaped steel beams with simulated crack and 80% corrosion damage. Saafi and Asa [63] also followed the wet lay-up method to impregnate an E-glass jacket with epoxy to repair 30-year-old circular wooden poles in Alabama, USA. The wet lay-up FRP composite jacket was 5 mm thick and wrapped around the pole for a length of 850 mm at 2 m distance from the bottom. Cantilever bending tests showed that the repaired poles can restore the load capacity by more than 85%. These studies showed that wet lay-up FRP wrapping is an effective technique in repairing deteriorated structures. This technique is also preferable when urgent rehabilitation is required but demands good work quality in terms of preparing and installing the FRP jacket. Moreover, if the repair work is underwater, it will be much more difficult to execute, monitor and cure the wet lay-up systems, especially when more than one layer is required. There are also safety concerns in the styrene emission while preparing the jacket which restricts the full employment of this technique [64]. Therefore, the prefabricated systems have been a preferred technique in rehabilitating structures under water or in areas that are hard to access.

Prefabricated composite repair systems are manufactured at specialized plants and delivered to a site in ready for installation packages. These repair systems are preferable to the wet lay-up technique as they are produced under well controlled manufacturing conditions, and are easier, quicker and safer to install and require less onsite labour [64,65]. Prefabricated FRP jackets are becoming widely used for regular and under water structural repairs as they serve as a permanent formwork and protective shield. The gap between the FRP shell and the treated structural

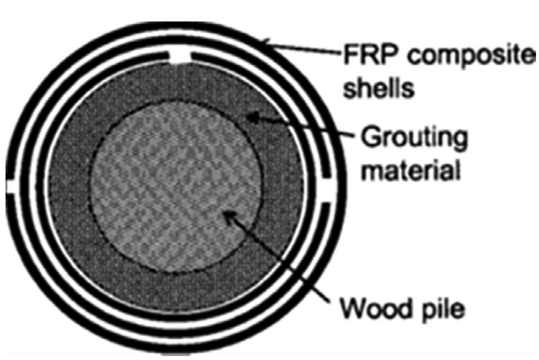


Fig. 4. Wood pile repair [21].

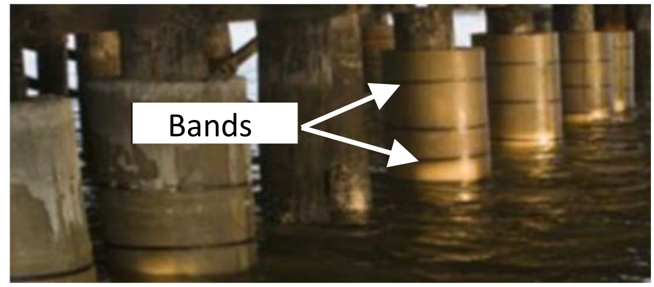


Fig. 5. Waterfront structure repair, New York [66].

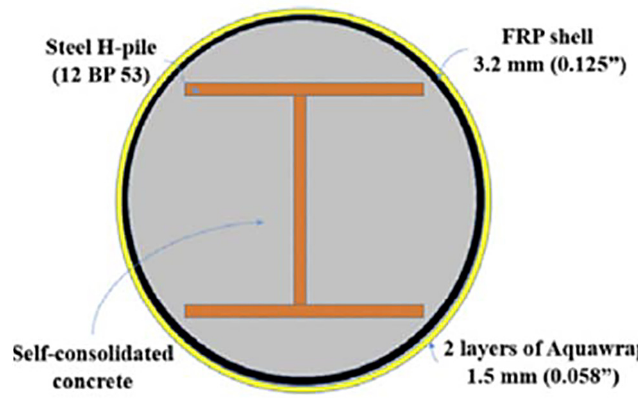


Fig. 6. Steel bridge pile repair [23].

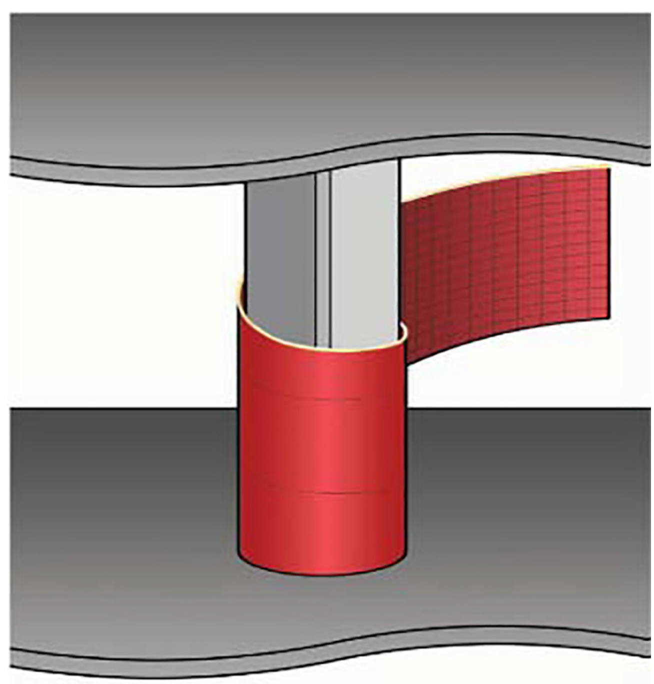


Fig. 7. PileMedic™ [67].

member is filled with non-shrink grout or concrete. Several examples are available in the literature [21,23,66–68] regarding this technique and these will be discussed in detail in the following sections.

Lopez-Anido et al. [21] suggested the use of 3.3 mm thick prefabricated FRP composite shells as a repair system to protect and restore the structural integrity of circular damaged wooden piles in Portland Harbor, Maine, USA (Fig. 4). The proposed repair system comprised a minimum of two FRP prefabricated shells which were kept together by straps or temporary strips along the circumferential direction. Another prefabricated FRP repair system consisting of woven mat and chopped strand fabrics with single seam FRP shell was used to repair waterfront structures in New York City as shown in Fig. 5 [66]. In addition to the strength contribution, both systems served as an environmental protective shield to the core pile and a permeant formwork to the grout.

Vijay et al. [23] used both pre-cured FRP shells and prepreg fabrics to repair the corroded H-steel piles of East Lynn Lake Campground Bridge in Wayne County, West Virginia USA (Fig. 6). Self-consolidating concrete was used to fill the gap between the FRP shells and the H-steel piles where the FRP shell worked as a permanent formwork to the grout. The installation process for this repair system required the prefabricated FRP shells to be installed first before applying the prepeg fabrics which needed a few days to cure prior to grouting. Hence, extended installation time and high manpower costs were incurred in this practice. Ehsani [67] developed the FRP seamless jacket PileMedic™, which consists of thin and flexible fabric laminates up to 1500 mm wide for pile repairs. However, it did not serve as a formwork in the construction of columns or piers because of their spiral wrapping method as shown in Fig. 7. Beddiar et al. [68] used a GFRP prefabricated jacket consisting of three identical shells connected together by stepped lap joints with shrinkage-compensating cement mortar as infill between the shells and the square column. The experimental results demonstrated that the axial load capacity and ductility increased by 31% and 74%, respectively, compared to the unjacketed concrete specimens. However, this came at the expense of 100% increase in the cross sectional area. Karagah et al. [69] implemented a large-scale experimental study to demonstrate the structural performance of submerged corroded I-shaped steel bridge piles repaired using two different types of grout-filled FRP jackets. The first one consisted of two plies of prefabricated flexible CFRP wrapped around the piles and bonded using an underwater curing adhesive. The second type consisted of a two-layered FRP system wherein the first layer was fabricated using two plies of GFRP installed around the pile using marine adhesive and screws, while the second layer consisted of one CFRP layer installed over the GFRP layer using a wet lay-up technique. The results showed that both repair systems were capable of restoring and enhancing the axial strength of the piles with the second type providing 11% higher enhancement than the first one.

Fig. 9. GFRP composite pile repair system [70].

Wu and Pantelides [25,26] proposed a rapid seismic repair method for RC bridge columns, which designed were designed under current codes, with minimal intervention. The repair method involves a CFRP cylindrical shell, epoxy-anchored headed steel bars, and steel collar with studs around the original column as shown in Fig. 8. The CFRP shell, consisting of unidirectional laminates in the hoop and vertical direction, encloses the headed bars and is filled with non-shrink concrete to shift the location of column plastic hinge. Vertical fibres were provided in the CFRP shell to increase tensile capacity of the shell in the axial direction to avoid the circumferential cracks [25,26,50]. Steel collar with shear studs improved the bond between original column and repair concrete to increase structural integrity of the whole CFRP "donut". Fig. 9 shows a prototype of a GFRP composite pile repair system

a) Steel collar and anchored steel b) CFRP jacket

Fig. 8. Seismic repair method [26].

Fig. 10. GFRP jacket [71].

that was successfully utilised for underwater repair trials of piles at the Missingham Bridge in Northern NSW, Australia in 2005 [70]. Fig. 10 depicts another FRP repair system with a tongue and grove joining system installed around bridge piles with metal screws being bolted through the joints. As shown in the summary of the existing prefabricated FRP repair systems presented in Table 1, the tongue and grove joining system with metal screws is the most common technique in the actual applications of the FRP repair system due to its ease and rapid fitment. However, the durability of the use of metal screws in the technique is always a concern as they do not have the same characteristics as the FRP shell in resisting the severe environmental conditions. The failure of the joining system results in opening of the jacket leading to its functional loss. Hence, the effectiveness of the prefabricated FRP composite jacket for repair of structures depends mostly on the joining technique as it is responsible to provide complete continuity for the repair system. Therefore, there is an urgent need to innovate an effective joining system for the prefabricated FRP repair system that can assure the structural continuity along the hoop direction.

4. Factors affecting structural repair using prefabricated FRP repair system

Prefabricated FRP repair systems work by placing the flexible FRP shell around the degraded structure and then filling the gap between the shell and the repaired structure with a non-shrink grout infill. The long-term effectiveness of the repair system mainly depends on the durability of the FRP jackets which depends on their inherent properties. Hollaway [74] presented durability considerations to effectively utilize FRP composites in various environments. For example, aramid fibres are not recommended be used in alkaline and acidic environments and UV exposure while careful consideration is suggested when using glass fibres in alkaline environment due to the presence of silica in the glass. On the other hand, carbon fibres are resistant to the ingress of alkali or solvents, but experience galvanic corrosion. Thus, the ACI-Committee [57] introduced an environmental reduction factor for FRP repair systems to account for the durability effects under different exposure conditions.

The structural effectiveness of the repair system is associated with several factors which have to be considered in the design of the repair system, including the conditions of the existing structures and the properties and dimensions of its components, i.e. FRP jacket, joining system and grouting system. The effect of these factors on the repair system is discussed as follows:

4.1. Condition of the existing structures

The condition of a deteriorated structure and the extent of its damage are critical parameters for assessment before proceeding with any repair strategy. It is also important to consider the existing site and environmental conditions prior to selecting an appropriate repair technique.

4.1.1. Environmental conditions

Structures in aggressive environments are susceptible to durability problems due to the external environmental attacks which affect their serviceability and structural reliability. Davis [75] classified the marine environment infrastructure (e.g. piles) into different zones: submerged (the part of pile extending from 0.3 m to 1.0 m below mean low tide to mud line), tidal (the part of pile extending between mean high tide and mean low tide which is subjected to wet-dry cycles), splash (the part of pile above the mean high tide where it is subjected to wetting by water drops) and atmospheric zones (the top part of the pile where it is subjected to minimal wetting by waves splash). The parts of structures located in the tidal region are considered to be the most critical members [76] since they are subjected to both physical and chemical attacks. Safehian and Ramezanianpour [77] also identified that the tidal and the splash zones are subjected to the most aggressive weathering attacks, which commonly cause reinforcement corrosion due to chloride ion ingress in the concrete [78]. Furthermore, the motion of waves and tides in the tidal zone cause physical collision, erosion and abrasion [79]. Steel structures in such environments are susceptible to section loss due to corrosion damage which degrades their structural performance [80,81]. For example, the East Lynn Lake Campground Bridge was narrowed to one traffic lane and then closed completely after finding steel section losses of up to 60% in its piles [23]. As another example, marine borers and organisms can cause extensive damage to wooden marine piles. In Portland Harbor, Maine, USA, several wooden piles were severely decayed due to the surrounding harsh environment and were classified as structurally deficient [21].

Aggressive soil and acid attacks are other types of harsh environments that cause significant structural degradation and loss of performance [82–86]. There are concerns about iron, steel and other metals being embedded in aggressive soils as they exhibit significant rates of corrosion. Montgomery [87] reported on another issue: severe sulphuric acid attack damaged the pile foundation of chemical plants located on the Atlantic coast of the USA, which resulted in up to 130 mm settlement of concrete columns. Concrete, however, would not have been seriously damaged by sulphate attacks if moderate sulphate resisting or highly sulphate resisting cement were to be used, depending on the extent of the exposure [88].

4.1.2. Level of damage

Corrosion of steel reinforcement is the most substantial degrading problem faced by RC structures. It is responsible for concrete cracking, bond strength weakening, loss in steel cross-section, and loss of serviceability and structural functionality [89–96]. Manalo et al. [97] indicated that simulating 50% steel corrosion in circular RC columns of 1 m height and 250 mm diameter

Table 1
Summary of FRP composite application in the laboratory and on real structures.

Reference	Description	Joining system	Level of Development	Advantages	Disadvantages
Lopez-Anido et al. [21]	Circular GFRP shells made of unidirectional E-glass layers (0° and 90°) and chop strand layer.	Two overlapping open shells strapped together.	R&D	Rapid installation Permanent formwork	Outer metal straps are susceptible deterioration which lead to jacket opening.
Van Erp et al. [70]	Circular GFRP composite pile repair system	Composite pins	Prototype	Rapid installation Permanent formwork	No continuity along the hoop
Williams [66]	Single seam circular GFRP jacket made up of chop strand and woven mat impregnated with epoxy resin.	Tongue and groove with metal screws	Application	Rapid installation Permanent formwork	Screws and outer bands are susceptible deterioration which lead to jacket opening.
Ehsani [67]	Thin, flexible and continuous GFRP jacket wrapped spirally along the pile.	Seamless jacket	Application	Rapid installation	This system cannot serve as a form work due to its wrapping technique.
Strong-Tie [71]	Round, H-pile, square/rectangular or octagonal GFRP jacket	Tongue and groove with metal screws	Application	Rapid installation Permanent formwork Various shapes	Screws are susceptible deterioration which lead to jacket opening.
Beddiar et al. [68]	Three identical GFRP segment bonded together to form a cylindrical shell.	Bonded stepped lap joint	R&D	Permanent formwork	Complex and poor continuity along the hoop
Vijay et al. [23]	Circular GFRP shells and prepreg GFRP fabrics for wrapping	GFRP prepreg fabrics wrapping	Application	Permanent formwork	Long installation time and high labour cost
Five Star [72]	Five Star PileForm round, H-pile or square/rectangular GFRP jackets	Tongue and groove with metal screws	Application	Rapid installation Permanent formwork Various shapes	Screws are susceptible deterioration which lead to jacket opening.
FiberSystems [73]	Combined carbon and glass FRP circular jacket	Bonded overlapping joint	Application	Rapid installation Permanent formwork	Poor continuity along the hoop
Karagah et al. [69]	CFRP or combined CFRP and GFRP jacket where the CFRP layer installed over the GFRP shell using wet lay-up technique.	Bonded overlapping joint	R&D	Rapid installation Permanent formwork	Poor continuity along the hoop
Wu and Pantelides [25,26]	CFRP cylindrical shell “donut” and epoxy-anchored headed steel bars	Bonded overlapping joint	R&D	Seismic repair Permanent formwork	Limited to columns’ ends repair due to the headed steel bars anchorage.

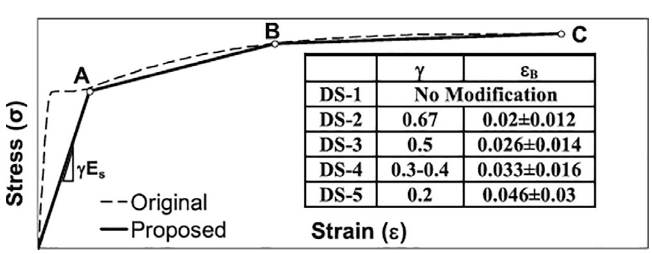


Fig. 11. Stress–strain curves.

resulted in 56% reduction in the axial load capacity due to the loss in the area of steel which resulted in a minor eccentricity effect. Experiments by Torres-Acosta et al. [94] showed that the increase in the depth of rebar corrosion damage was the most significant parameter in reducing the flexural strength of corroded RC beams as it initiates localised failure. The exposed reinforcement due to concrete cover spalling affects the structural performance of the damaged member because the reinforcement loses its structural integrity and composite action with concrete. A study carried out by Cairns and Zhao [98] showed that in a rectangular beam with no concrete cover at the bottom, 50% loss in flexural capacity was found due to bond strength loss between the steel and the concrete. In another study, Vosooghi and Saiidi [30] developed a trilinear stress–strain relationship (Fig. 11) to estimate the existing strain in the longitudinal bars of damaged columns based on five visual damage states (DS) that were defined as follow: DS-1 (flexural cracks), DS-2 (minimal spalling and possible shear cracks), DS-3 (extensive cracks and spalling), DS-4 (visible lateral and/or longitudinal reinforcing bars), and DS-5 [compressive failure of the concrete core edge with only a few longitudinal bars may exhibit slight buckling (imminent failure)]. A reduction factor was used, based on the damage state, to modify the original slope of the first branch of Fig. 11. In the same figure, Point A represents the yield stress and the strain associated with the modified stiffness, Point B is associated with the maximum strain in the longitudinal steel at a given damage state, and Point C is the modified ultimate point accounting for strain rate effect. Another important factor to consider in the repair is the bond slip effects of the existing steel bars if they were still embedded in the damaged concrete [99], or directly interact with new and confined concrete [100]. Harajli [99] developed a bond-slip relationship predicting the bond degradation response of bond-critical regions in reinforced concrete members when retrofitted using external FRP jackets including the effects of steel bar diameter, ratio of concrete cover and concrete compressive strength. Moreover, Wu and Pantelides [100] incorporated the effect of bond-slip in the model they developed to accurately simulate the seismic performance of repaired column-to-cap beam/footing connections using CFRP jacket.

Steel structures, and even galvanised steel after the consumption of galvanic protection, will corrode, when exposed to harsh environments, and their strength capacity is reduced accordingly. Beaulieu et al. [101] reported that 25% and 40% simulated corrosion in steel angle members resulted in a decrease by 24% and 42%, respectively, of their compressive strength due to the loss in the cross sectional area. For timber structures, wooden piles with more than 50% loss in their cross-sectional area need to be replaced as it is hard to estimate the residual strength capacity of degraded structures and decide when they are no longer safe [102]. Pizzo et al. [103] observed an average reduction of 70% in residual compressive strength of decayed wooden piles due to the mass loss and the alteration in chemical composition of the wood. These results are in agreement with those established by Klaassen [104] and Schniewind [105]. The repairability threshold is driven by the results of the initial repair design where the residual strength of the original section is assessed and the additional strength from the FRP repair system is calculated. The summation of both is then compared with the design load. The economic aspect is also considered as another criteria for the repair. An appropriate, cost-effective, reliable, and safe repair system is therefore needed to restore the capacity of such deteriorating structures to an acceptable level of service.

4.2. FRP composite jacket

Thickness, fibre type and fibre orientation are the three main material parameters that influence the effectiveness of an FRP jacket system. This section discusses how each parameter affects the behaviour of an FRP jacket.

4.2.1. Thickness

The FRP jacket thickness has substantial effects on the strength and ductility of repaired columns. In addition, it is directly related with the exerted confinement pressure of the FRP jacket as the confinement effectiveness increases with higher thickness [106]. Berthet et al. [107] and Li et al. [108] indicated that FRP wraps with higher thickness significantly enhance the strength and ductility of wrapped concrete columns. A study conducted by Hajsadeghi et al. [51] showed that concrete columns wrapped with five FRP sheets had higher axial stress and axial strain capacity in comparison with the columns wrapped with one or three layers because of the increase in the confining pressure with the increase in thickness. Other research by Parvin and Jamwal [109] revealed that the axial strength increased with the increase of the wrap thickness for all FRP-wrapped columns. On the other hand, the average hoop strain decreases as the number of sheets or the thickness of FRP jackets is

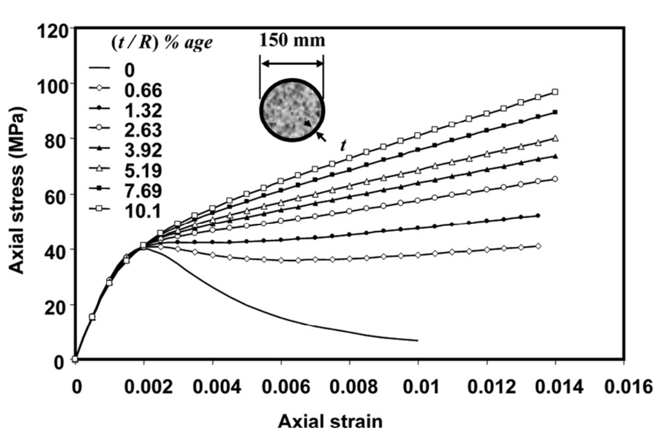


Fig. 12. Stress–strain curves of confined concrete with FRP tubes of various thickness [115].

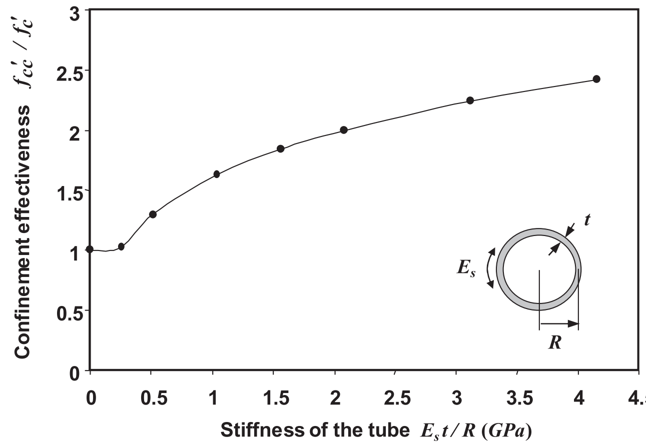


Fig. 13. Confinement effectiveness of FRP tubes with various stiffness [115].

increased because they are inversely related [110,111]. This effect was also demonstrated by Fam and Rizkalla [112] as shown in the Figs. 12 and 13. Increasing the FRP jacket thickness has the same effect on steel and timber structures because the exerted confining pressure is what matters the most [63,113]. However, for hollow steel tubes, Teng et al. [113] indicated that once the thickness of jacket reaches a specific threshold for which the dominant behaviour is the inward buckling deformations of the hollow steel tube, an additional increase in the thickness of jacket will not result in noteworthy further benefits as the jacket does not provide good resistance to inward buckling deformations [113].

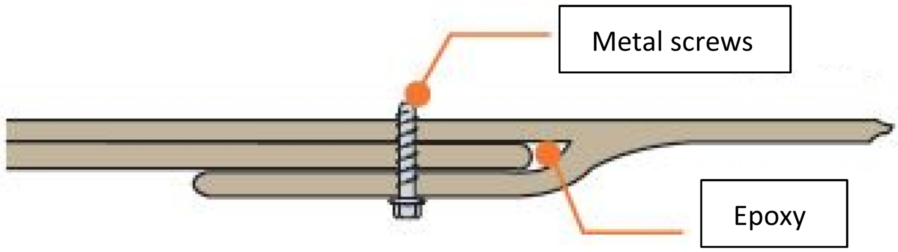
Regarding the thickness of prefabricated and ready-to-install FRP jackets, there is no specified upper limit value since they are manufactured in specialised plants as one integral part. However, there is a limitation on the thickness of multilayer FRP laminate strengthening system as additional layers increase the number of potential failure modes because failure can occur in the adhesive between each layer which increases the risk of failure within the FRP. For example, VicRoads [114] limits the layers of FRP strengthening system to maximum of 2 layers for pultruded plates, and 3 layers for FRP fabrics.

4.2.2. Fibre type and orientation

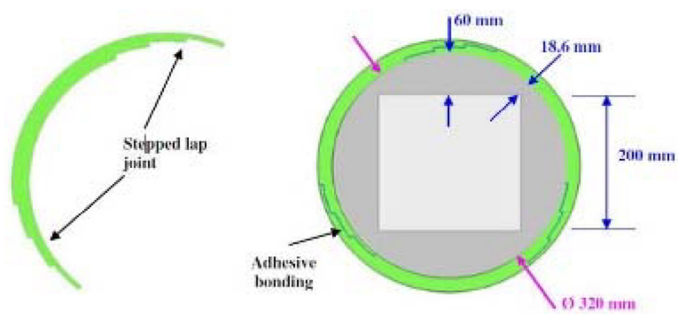
The magnitude of the confining stresses exerted by the prefabricated FRP jacket is the main factor that affects the repair system effectiveness, and it is highly influenced by the fibres' type and orientation regardless of the core material type whether it is concrete, steel or timber [116–119]. For example, glass fibres are more cost competitive than carbon fibres, but the latter have superior characteristics, while aramid fibres have lower compressive load capacities compared to other fibre types [52]. Fibres are oriented along the load direction to resist axial loads. However, in prefabricated FRP jackets, fibres are oriented in the circumference direction to produce higher lateral stresses which, in return, results in higher axial load capacity. Moreover, additional fibres with an inclination of various angles with respect to the hoop and longitudinal directions are used to provide resistance against multi-axial strains, increase the structural integrity of the whole FRP shell and behave in a more ductile manner at failure [26,51]. Finally, increasing the confining pressure significantly increases the ductility enhancement ratio [106,107,120].

4.3. Joining system

Many techniques were adopted to join the jacket's ends and encapsulate the damaged member. The type of joining system



a) Tongue-and-groove joining technique [121]



b) Stepped lap [68]

Fig. 14. Joining systems.

can affect the durability and the utilisation limit of the repair system. For example, the joint will have different capacities to resist the weathering and environmental attack if it was made from materials different to that of the jacket body. The premature jacket failure limits the full utilisation of the FRP repair system. Many joining systems were proposed and designed in a way to address the aforementioned concerns; however, their performances varied significantly from each other.

In the repair system proposed by Lopez-Anido et al. [21], the splits in FRP shells were aligned away from each other to avoid a weakness line along the entire height of the shell. The interior surface of each shell was glued to the outer surface of the next shell using epoxy. Circumferential metal straps or temporary bands were then used to hold the shells together and achieve the structural restoration. As shown in Fig. 14a, slip-joint/tongue-and-groove is another popular joining technique to connect the ends of the FRP jacket [121]. Epoxy and self-taping metal screws were also used to hold the tongue in the groove and increase the reliability of the joint. This technique was adopted to repair waterfront structures in New York City [66]. In addition, steel bands were used in the adopted repair system to hold the jacket and contain the infill. The metal screws damage the FRP shell and affect the stress flow by developing stress concentration regions which eventually affect the fatigue resistance and the lifespan of the FRP shell. Another method is that used by Vijay et al. [23] where additional water-curable GFRP prepregs were applied on the outer surface of the FRP shell to keep jacket ends together and prevent them from opening. An alternative seamless FRP repair system was proposed by Ehsani [67] consisted of flexible FRP laminates that can be spirally wrapped around the damaged member. Finally, a stepped lap joint technique was proposed and used by Beddiar et al. [68] to join the FRP jacket ends together (Fig. 14b). Each step was measured to be 40 mm in length to provide sufficient overlapping for the jacket ends in addition to being glued together using epoxy.

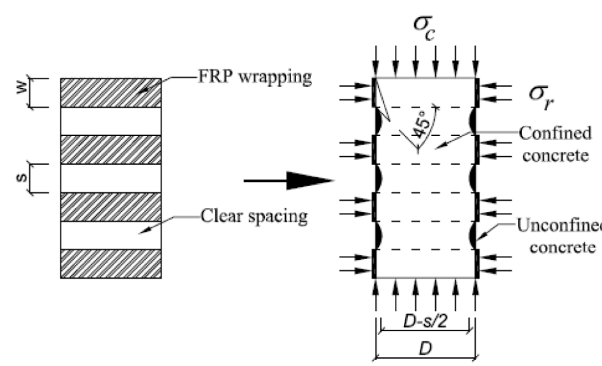
There are concerns about the capability of commercially available prefabricated FRP repair systems to provide effective structural continuity and actual confinement in the hoop direction. For instance, the joint and the bands consisting of metallic material are prone to corrosion. Moreover, using extra FRP layers and/or epoxy increases the installation time as they require additional time to cure, which increases the installation/labour cost. These limitations can be overcome by integrating an innovative and sustainable joining system with the FRP jacket.

4.4. Grouting system

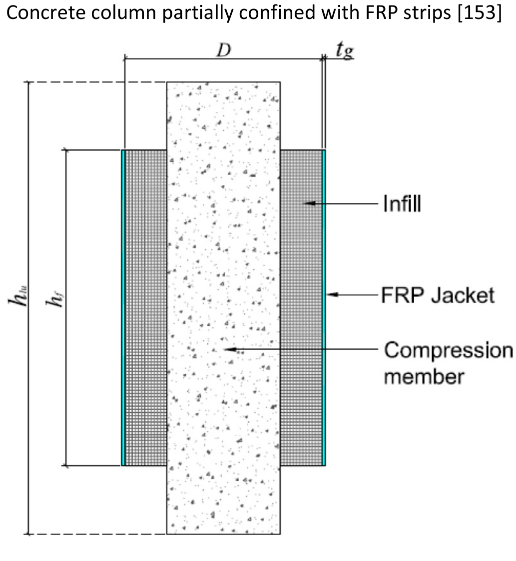
Studies on the effect of grouting systems on the effectiveness of prefabricated FRP repair systems are limited. However, the grout is a key player in transferring the stresses between the damaged core and the outer FRP shell and developing the composite action within the repair system. The functionality of the grout, with regard to load transferability and effective employment of the FRP jacket, is dependent on its compressive strength and modulus of elasticity [23,122,123]. Grout thickness, on the other hand, is insignificant in the case of a grout with stiffness higher than 20 GPa, while in the case of a low stiffness grout, the thinner grout is better than thicker grout for bringing together an effective composite action among different components of the jacket system, thus producing lower strains in the core [124]. Mohammed et al. [122] revealed that the behaviour of the prefabricated FRP jacket is strongly affected by the compressive strength and the modulus of elasticity of the infill. Localised failure was observed in the FRP repair system due to the brittle cracking and crushing behaviour of the cementitious and epoxy grouts while the progressive failure of the concrete infill resulted in effective utilisation of the high strength characteristics of the FRP repair system. The authors also concluded that the high compressive strength of the grout infill restrained its ability to transfer the stresses uniformly around the

FRP jacket due to increased brittleness. The numerical analyses conducted by Sum and Leong [125] showed that increasing the epoxy grout stiffness resulted in better stress transfer and more effective utilisation of the composite sleeve as a repair system for high pressure steel pipelines due to the enhanced composite action of the repair system. In another study, Deb and Bhattacharyya [126] highlighted the importance of the bond strength between the infill and the FRP shell as it can influence the effectiveness of the prefabricated FRP jacket because any discontinuity or voids presence would induce non-uniform stresses in the FRP shell leading to premature failure.

The grout is a vital part in the FRP repair system as it provides a smooth surface for the FRP shell and refill of the lost profile of the damaged structure which will assure a full contact among the components of repair system [123]. In addition, the grout infill is necessary when the original structure requires shape modification, i.e. from square or rectangular to a circular section for more effective confinement [127–129]. In order to eliminate separation from the FRP shell due to shrinkage, Fam and Rizkalla [115] used expansive cement in the concrete fill to fully engage the tube from the onset of applying the system through some active confinement. It is important therefore that the effect of these parameters are considered in the design of a prefabricated FRP repair system.



a) Concrete column partially confined with FRP strips [153]



b) Concrete column partially confined with one FRP segment [161]

Fig. 15. Confinement mechanism.

5. Existing models to evaluate effectiveness of prefabricated FRP repair systems

It is well established that using an FRP jacket to laterally confine the concrete significantly increases its strength and ductility. Over the last two decades, substantial amounts of research have been carried out to understand and model the axial behaviour of FRP-confined concrete. As a result, about 80 stress–strain models have been developed [120,130] considering the various shapes of columns, i.e. square, rectangular, circular and elliptical [131,132]. The majority of the available models can be categorised into two groups as suggested by Lam and Teng [120]: (a) design-oriented models [133–142], and (b) analysis-oriented models [115,143–151]. In design-oriented models, the compressive strength, ultimate strain and stress–strain behaviour are predicted using closed-form equations based directly on the interpretation of experimental results. In analysis-oriented models, stress–strain curves are generated using an incremental numerical procedure to capture the interaction between the FRP jacket and concrete core. They are, therefore, more appropriate for incorporation in non-linear finite element analysis in computer-based numerical analysis software [120]. In contrast, design-oriented models are specifically suitable for direct implementation in design calculations as they offer an approach that is familiar to engineers for calculating the strength of FRP-confined RC structures. Hence, the design-oriented models are widely adopted in repair system applications.

Most of the previous research work on RC columns retrofitting using FRP composites, focused on columns wrapped fully with FRP jackets to assure the confinement continuity along their longitudinal axes [111,152]. Only a small number of studies investigated columns wrapped partially with FRP composites yet also showed an increase in strength and ductility, in comparison with equivalent unconfined columns [153–157]. However, concrete columns partially confined with FRP composite are less efficient in nature than fully-confined columns due to the presence of the unconfined areas along their heights (Fig. 15a). Mander et al. [158] proposed a model to determine the effective confining pressure on the concrete core, and it has been utilised in several subsequent studies [153,159,160]. Fig. 15a shows the effectively confined areas of the concrete core where the confining pressure is assumed to be fully developed due to arching action. The arching effect is described with assumed second-degree parabola with initial slope of 45°. Hence, a confinement effective coefficient (k_e) is introduced to consider the partial wrapping effects as shown in Eq. (1):

$$k_e = \frac{A_e}{A_c} = \left(1 - \frac{s}{2D}\right)^2 \tag{1}$$

where A_c and A_e are the cross-sectional area and the effectively confined concrete area respectively; s is the clear spacing between two FRP strips and D is the diameter. Consequently, the active confining pressure ($\sigma_{l,a}$) on the columns wrapped partially with FRP composites can be calculated as stated in Eq. (2):

$$\sigma_{l,a} = \frac{2t_g E_f \varepsilon_{hu}}{D} \times k_e \tag{2}$$

where the first term accounts for the jacket properties as t_g is the nominal thickness of FRP jacket; Ef is the elastic modulus of FRP; and ε_{hu} is the rupture strain of FRP in the hoop direction. However, since the partial confinement in most pile repair systems is carried out using one large FRP segment as mentioned in the existing literature, Mohammed et al. [161] proposed a confinement effective coefficient (h_f/h_{lu}) considering the height of the FRP jacket (h_f) and the total height of the column (h_{lu}) instead of the confined area (Fig. 15b) to predict the maximum axial load of the damaged RC concrete columns repaired using prefabricated FRP jackets and cementitious infill. The active confining pressure on the concrete columns wrapped partially with one FRP segment was calculated as stated in Eq. (3):

$$\sigma_{l,a} = \frac{2t_g E_f \varepsilon_{hu}}{D} \times \frac{h_f}{h_{lu}} \tag{3}$$

Moreover, the model developed by Mohammed et al. [161] considered the level of damage in the original structure while predicting the axial strength of the repaired column as detailed in Eq. (4)

$$\sigma_{cc} = \sigma_{co} + \left(\frac{5t_g E_f \varepsilon_{hu}}{d_{gi}} \times \frac{h_f}{h_{lu}} - 1.3\sigma_{co}\right) \times \left[1.22\left(\frac{A_{ef}}{A_{undamaged}}\right) - 1.28\right] \tag{4}$$

where σ_{cc} and σ_{co} are the predicted and the original compressive strength of the column, respectively, and A_{ef} and $A_{undamaged}$ are the normalised effective area and the original area, respectively. Moreover, the jacket strain at the moment of joint failure was considered, while the grout was considered to be of the same material type as that of the core. This model showed a close agreement between the experimental and the predicted values of the repaired RC columns. However, the developed theoretical model might be only applicable to the prefabricated FRP repair system investigated in that research and further verification and/or calibrations are recommended for other different types of repair systems with different core materials, i.e. steel or timber.

Finally, for the steel structures, there are several models available to predict their strength and behaviour when strengthened with FRP wrapping [113,162–165], but there are no theoretical models to predict the behaviour and/or strength capacity of damaged steel structures repaired with prefabricated FRP jackets, and similarly for timber structures. Hence, further theoretical investigation in the area of repairing steel and timber structures using prefabricated FRP repair system is recommended.

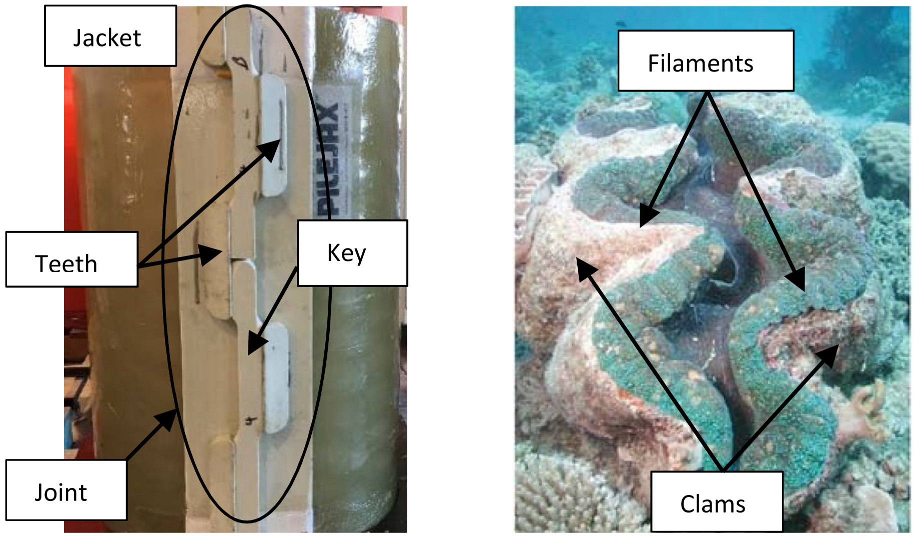
6. Discussion and future research

The damage level of existing structures is closely associated with the severity of the surrounding environmental conditions. The highest level of damage is found at the tidal zones as those areas are subjected to both physical (waves) and chemical attacks (chloride ion ingress). RC and steel jackets are commonly used to repair these damaged structures despite the fact that they are heavy and bulky repair systems. They also significantly increase the size and weight of the retrofitted member which is not desirable, especially during seismic events, as they tend to attract higher loads due to their increased rigidity [44]. Furthermore, using the same original material for repair with the presence of the same environment will cause similar damage again and the repair cycle may never end. Hence, more research is being conducted to use the prefabricated FRP composite jackets in structural repair to overcome the drawbacks of using traditional materials in a repair system.

The effectiveness of the prefabricated repair system depends on the properties of the jacket (thickness, fibre type and orientation) and its joining system to maintain the jacket continuity around the damaged member. The confinement effectiveness increases with the increase of the jacket's thickness as the exerted confinement pressure is higher for thicker jackets [106]. Carbon fibres are also used when higher effectiveness is required because they have superior properties compared to those of glass and aramid fibres, and they are oriented along the circumference axis [52]. The grout, on the other hand, is essential to connect the repair system components by transferring the loads between the damaged core and the composite FRP shell. The grout's compressive strength and modulus of elasticity [23,122,123] are the two critical mechanical properties that affect its functionality in terms of load transferability and effective utilisation of the FRP system. High compressive strength grout reduces the repair system effectiveness as it has limited capacity in transferring the load uniformly due to the increased brittleness. Further research considering various types of cost-effective grouts with a different range of properties should be conducted to optimise the design and utilisation of the repair system.

Interestingly, the original compressive strength of the core material can affect the strength gain of the confined structure. The very low strength confined concrete experience severe crushing under axial load [122]. In the developing countries, the very low strength concrete is commonly used in RC structures where it should be noted that the concrete core can be significantly damaged without any remarkable deformation in FRP jacket which will not result in any additional axial load carrying capacity for the repaired column despite the use of confining jackets. For normal strength confined cores (20–50 MPa), the strength gains depend only on the confinement pressure generated by FRP jackets and it increases with higher confinement pressure. In case of high strength cores, the strength gain is a function of both the confinement ratio and the maximum compressive strength of the core. The strength gain, however, decreases marginally with the increase in the compressive strength of the core. In the same way, the hoop strain capacity of the FRP shell declines as the core's compressive strength increases. The main reason for the decline is the high material brittleness which increases with the core compressive strength regardless of its type i.e., concrete, steel or timber. In concrete, the increased brittleness drives the micro-cracks to be developed in heterogeneous manner which is considered the main reason for this deficiency [110], while in steel and timber, the increased brittleness decreases the Poisson's ratio effects and more internal stresses will be generated resulting in local failure of the core and consequently of the FRP jacket. Moreover, the original shape of the core structure can affect the overall behaviour of the repaired structure as several studies showed that the confinement mechanism of prefabricated FRP shells is less competent for square/rectangular columns in comparison with circular columns [68,100,130]. Prefabricated FRP composite jackets have an excellent in-plane tensile strength but, as they are quite thin, possess relatively small out-of-plane bending strength. Hence, the tensile hoop stresses in the composite jacket generate confining pressure that uniformly confines the whole area of a circular column. At the same time, non-uniform confining pressures are exerted by the prefabricated FRP jackets onto square/rectangular cross sections. Concentrated confining pressures are generated at the corners of square/rectangular columns rather than on the sides because confining pressures on the sides result from the flexural behaviour of the composite shell rather than its behaviour in tension [58]. Nevertheless, there are concerns about the ability of the commercially available prefabricated FRP repair systems to provide effective structural continuity and actual confinement in the hoop direction. These concerns have motivated the development of a prefabricated FRP repair system with an easy-fit and self-locking mechanical joining system (Fig. 16). The novel joining system consists of two interlocking edges and a locking key to provide a uniform force distribution along the entire height of the joint. This joint design was inspired by the way in which clams attach themselves to rock ledges using anchors through hundreds of small filaments. These filaments can produce a strong hold when their strength is combined (Fig. 16b).

Manalo et al. [64] identified the most effective joint materials that can provide a scenario of structural continuity in the hoop direction and effective confinement to the repaired structure. Mohammed et al. [161] conducted a large-scale experimental investigation to evaluate the effectiveness of the novel FRP repair



a) Composite pile repair system b) The clam concept

Fig. 16. The prefabricated composite pile repair system.

Fig. 17. Bridge piles repaired with FRP jacket [166].

system in repairing RC concrete piles. Concrete columns with simulated steel corrosion and concrete cover damage were repaired with an FRP jacket that partially covered the columns' height. The gap between the pile and the jacket was filled with grout prior to axial compressive loading of the test specimens. The compression testing results showed that FRP jacket could restore the stiffness and the axial strength capacity of the damaged columns to the original levels of the undamaged columns [161]. This repair system has been successfully used to rehabilitate a road bridge located at the Gold Coast in Queensland, Australia (Fig. 17). It was chosen over other rehabilitation jackets for its benefits: cost-effectiveness, rapid fitment, safety, and ease of installation [166]. Mohammed et al. [161] however recommended further modifications on the current joining system design to fully utilise the jacket capacity and expand the application of the prefabricated repair system to strengthening situations.

Important parameters such corrosion level, concrete cover loss, shape, grout infill properties, jacket thickness and the integrity of the joint should be taken into consideration while designing and constructing using the prefabricated FRP repair system. The cost effective prefabricated composite jacket is being further explored and investigated with a focus on developing the next generation of efficient and reliable structural composite repair methods. The current model for damaged RC columns repaired with prefabricated jacket can be developed further to include additional factors like the type of grouting system and the degree of damage within the core structure.

7. Conclusions

This paper critically reviews the existing jacketing techniques to repair and strengthen existing damaged or deteriorating infrastructure. It focuses on prefabricated FRP composite jackets and identifies the parameters that affect the effectiveness of this type of repair system. From this critical review, the following conclusions and recommendations can be drawn:

- Repairing the damaged structures using either concrete or steel jackets or timber splicing is impractical in infrastructure exposed to aggressive environments. Using these conventional materials will lead to never-ending repair cycles as they are subjected to the same environment which caused damage to the existing structure.
- FRP composite jacketing systems offer superior properties in terms of corrosion resistance, lightweight and durability compared to conventional repair systems and are compatible with steel, concrete and timber structures.
- Prefabricated FRP composite repair systems are preferable to the wet lay-up as the former systems are easier, quicker, safer to install, require fewer workers on site, lead to less resource wastage and have higher quality as they are manufactured under well controlled conditions.
- The design of an effective joint is key to providing structural continuity for prefabricated FRP composite jackets. The joining schemes should offer a composite repair system that is easy, quick and safe to install, and can be easily implemented for prefabricated FRP repair systems.
- The effectiveness of the prefabricated FRP composite jackets is governed by the thickness and orientation of the fibres within the jacket, the type and properties of infill grout, and the level

of damage and shape of the existing structures. Understanding the effects of these design parameters will lead to an optimal and safe design of prefabricated FRP jacket repair systems.
- Available models to predict the strength and behaviour of strengthened structures with FRP composite jackets do not account for the level of damage in the existing structures. The development of numerical and/or analytical models that systematically consider the effect of key parameters upon the overall response of repaired structures is needed to achieve a reliable and safe repair system.

From the above findings, the prefabricated composite jacket with an innovative joining system can be a game charger in the construction industry and can breathe new life into key infrastructure. The low cost-to-performance benefits of this type of repair system should be fully explored and its contribution to the structural capacity of the repaired structure should be determined. Next generation joining schemes with FRP prefabricated systems can offer a rapid and effective repair solution for deteriorating and structurally deficient structures.

Declaration of Competing Interest

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

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References

[1] X. Shi, N. Xie, K. Fortune, J. Gong, Durability of steel reinforced concrete in chloride environments: An overview, Constr. Build. Mater. 30 (2012) 125–138.
[2] S.A. Mangi, M.H. Wan Ibrahim, N. Jamaluddin, M.F. Arshad, S. Shahidan, Performances of concrete containing coal bottom ash with different fineness as a supplementary cementitious material exposed to seawater, Eng. Sci. Technol. Int. J. 22 (3) (2019) 929–938.
[3] A. Shayan, A. Xu, Realising 100-year bridge design life in an aggressive environment: review of the literature, 2016.
[4] G. Nkurunziza, A. Debaiky, P. Cousin, B. Benmokrane, Durability of GFRP bars: A critical review of the literature, Prog. Struct. Mat. Eng. 7 (4) (2005) 194–209.
[5] M. Cassidy, J. Waldie, S. Palanisamy, A Method to Estimate the Cost of Corrosion for Australian Defence Force Aircraft, (2015).
[6] M. Jumaat, M. Kabir, M. Obaydullah, A review of the repair of reinforced concrete beams, J. Appl. Sci. Res. 2 (6) (2006) 317–326.
[7] B.J. Bett, R.E. Klingner, J.O. Jirsa, Lateral load response of strengthened and repaired reinforced concrete columns, Struct. J. 85 (5) (1988) 499–508.
[8] S. Dritsos, C. Taylor, K. Vandoros, Seismic strengthening of reinforced concrete structures by concrete jacketing, Proceedings of the 7th International Conference on Structural Faults and Repair, 1997, pp. 391-402.
[9] U. Ersoy, A.T. Tankut, R. Suleiman, Behavior of jacketed columns, Struct. J. 90 (3) (1993) 288–293.
[10] M.M. Kassem, F. Mohamed Nazri, E. Noroozinejad Farsangi, On the quantification of collapse margin of a retrofitted university building in Beirut using a probabilistic approach, Eng. Sci. Technol. Int. J. 23 (2020) 373–381.
[11] R. Su, L. Wang, Axial strengthening of preloaded rectangular concrete columns by precambered steel plates, Eng. Struct. 38 (2012) 42–52.
[12] J. Garzón-Roca, J. Ruiz-Pinilla, J.M. Adam, P.A. Calderón, An experimental study on steel-caged RC columns subjected to axial force and bending moment, Eng. Struct. 33 (2) (2011) 580–590.
[13] J. Li, J. Gong, L. Wang, Seismic behavior of corrosion-damaged reinforced concrete columns strengthened using combined carbon fiber-reinforced polymer and steel jacket, Constr. Build. Mater. 23 (7) (2009) 2653–2663.
[14] A.S. Abdel-Hay, Y.A.G. Fawzy, Behavior of partially defected R.C columns strengthened using steel jackets, HBRC J. 11 (2) (2015) 194–200.
[15] İ. Demir, S. Güzelkücük, Ö. Sevim, Effects of sulfate on cement mortar with hybrid pozzolan substitution, Eng. Sci. Technol. Int. J. 21 (3) (2018) 275–283.
[16] Y.J. Kim, State of the practice of FRP composites in highway bridges, Eng. Struct. 179 (2019) 1–8.
[17] E. Guades, T. Aravinthan, M. Islam, A. Manalo, A review on the driving performance of FRP composite piles, Compos. Struct. 94 (6) (2012) 1932–1942.
[18] L.C. Hollaway, J.-G. Teng, Strengthening and Rehabilitation of Civil Infrastructures using Fibre-Reinforced Polymer (FRP) Composites, Elsevier, 2008.
[19] R. Sen, G. Mullins, Application of FRP composites for underwater piles repair, Compos. B Eng. 38 (5) (2007) 751–758.
[20] F. Faleschini, J. Gonzalez-Libreros, M.A. Zanini, L. Hofer, L. Sneed, C. Pellegrino, Repair of severely-damaged RC exterior beam-column joints with FRP and FRCM composites, Compos. Struct. 207 (2019) 352–363.
[21] R. Lopez-Anido, A.P. Michael, T.C. Sandford, B. Goodell, Repair of wood piles using prefabricated fiber-reinforced polymer composite shells, J. Perform. Constr. Facil 19 (1) (2005) 78–87.
[22] A.C. Manalo, A.A. Mohammed, G. Maranan, in: Novel Composites Jacket for Repair of Concrete Columns, Special Publication 327, 2018, p. 12.
[23] P. Vijay, P.R. Soti, H.V. GangaRao, R.G. Lampo, J.D. Clarkson, Repair and Strengthening of Submerged Steel Piles Using GFRP Composites, J. Bridge Eng. (2016). 04016038.
[24] A.A. Mohammed, A.C. Manalo, G.B. Maranan, M. Muttashar, Y. Zhuge, P. Vijay, J. Pettigrew, Effectiveness of a novel composite jacket in repairing damaged reinforced concrete structures subject to flexural loads, Compos. Struct. (2019). 111634.
[25] R.-Y. Wu, C.P. Pantelides, Rapid seismic repair of reinforced concrete bridge columns, ACI Struct. J. 114 (5) (2017) 1339.
[26] R.-Y. Wu, C.P. Pantelides, Rapid repair and replacement of earthquake-damaged concrete columns using plastic hinge relocation, Compos. Struct. 180 (2017) 467–483.
[27] R.-Y. Wu, C.P. Pantelides, Seismic evaluation of repaired multi-column bridge bent using static and dynamic analysis, Constr. Build. Mater. 208 (2019) 792–807.
[28] R.D. Iacobucci, S.A. Sheikh, O. Bayrak, Retrofit of square concrete columns with carbon fiber-reinforced polymer for seismic resistance, Struct. J. 100 (6) (2003) 785–794.
[29] A. Balsamo, A. Colombo, G. Manfredi, P. Negro, A. Prota, Seismic behavior of a full-scale RC frame repaired using CFRP laminates, Eng. Struct. 27 (5) (2005) 769–780.
[30] A. Vosooghi, M.S. Saiidi, Design guidelines for rapid repair of earthquake-damaged circular RC bridge columns using CFRP, J. Bridge Eng. 18 (9) (2012) 827–836.
[31] C.P. Pantelides, J. Gergely, Carbon-fiber-reinforced polymer seismic retrofit of RC bridge bent: Design and in situ validation, J. Compos. Constr. 6 (1) (2002) 52–60.
[32] Ö. zgür Yurdakul, Ö. Avşar, Structural repairing of damaged reinforced concrete beam-column assemblies with CFRPs, Struct. Eng. Mech. 54 (3) (2015) 521–543.
[33] Ö. Yurdakul, O. Tunaboyu, L. Routil, Ö. Avşar, Stochastic-Based Nonlinear Numerical Modeling of Shear Critical RC Beam Repaired with Bonded CFRP Sheets, J. Compos. Constr. 23 (5) (2019) 04019042.
[34] M. Gholami, A.R.M. Sam, J.M. Yatim, M.M. Tahir, A review on steel/CFRP strengthening systems focusing environmental performance, Constr. Build. Mater. 47 (2013) 301–310.
[35] F. Klaiber, K. Dunker, T. Wipf, W. Sanders Jr, Methods of strengthening existing highway bridges, Transportation Research Board, Washington, D.C., 1987.
[36] R.K. Lumor, J.S. Ankrah, S. Bawa, E.A. Dadzie, O. Osei, Rehabilitation of timber bridges in Ghana with case studies of the Kaase Modular Timber Bridge, Eng. Fail. Anal. 82 (2017) 514–524.
[37] M. Hawkswood, Marine Pile Repairs by Concrete Encasement, Innovative Coastal Zone Management, ICE, Belfast UK, 2011.
[38] N. Islam, M. Hoque, Strengthening of reinforced concrete columns by steel jacketing: a state of review, Asian Trans. Eng. (ATE ISSN: 2221–4267) 5 (2015).
[39] A. Tarabia, H. Albakry, Strengthening of RC columns by steel angles and strips, Alexandria Engineering Journal 53 (3) (2014) 615–626.
[40] V. Badalamenti, G. Campione, M.L. Mangiavillano, Simplified model for compressive behavior of concrete columns strengthened by steel angles and strips, J. Eng. Mech. 136 (2) (2009) 230–238.
[41] E. Choi, Y.-S. Chung, K. Park, J.-S. Jeon, Effect of steel wrapping jackets on the bond strength of concrete and the lateral performance of circular RC columns, Eng. Struct. 48 (2013) 43–54.
[42] N. Areemit N. Faeksin P. Niyom P. Phonsak Strengthening of deficient RC columns by steel angles and battens under axial load Proceedings of the Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), The Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13) 2013 pp. I-5-6.

[43] J.M. Adam, S. Ivorra, F.J. Pallarés, E. Giménez, P.A. Calderón, Axially loaded RC columns strengthened by steel caging finite element modelling, Constr. Build. Mater. 23 (6) (2009) 2265–2276.
[44] S.P.B. Waghmare, Materials and jacketing technique for retrofitting of structures, Int. J. Adv. Eng. Res. Studies 1 (1) (2011) 15–19.
[45] N. Delatte, Failure, Distress and Repair of Concrete Structures, Elsevier, 2009.
[46] M. Sakr, M. El Naggar, M. Nehdi, Interface characteristics and laboratory constructability tests of novel fiber-reinforced polymer/concrete piles, J. Compos. Constr. 9 (3) (2005) 274–283.
[47] S. Pessiki, K.A. Harries, J.T. Kestner, R. Sause, J.M. Ricles, Axial behavior of reinforced concrete columns confined with FRP jackets, J. Compos. Constr. 5 (4) (2001) 237–245.
[48] J. Teng, J. Chen, S.T. Smith, L. Lam, Behaviour and strength of FRP-strengthened RC structures: a state-of-the-art review, Proceedings of the institution of civil engineers-structures and buildings 156(1) (2003) 51-62.
[49] A. Manalo, C. Sirimanna, W. Karunasena, L. McGarva, P. Falzon, Pre-impregnated carbon fibre reinforced composite system for patch repair of steel I-beams, Constr. Build. Mater. 105 (2016) 365–376.
[50] J.E. Parks, D.N. Brown, M. Ameli, C.P. Pantelides, Seismic repair of severely damaged precast reinforced concrete bridge columns connected with grouted splice sleeves, ACI Struct. J. 113 (3) (2016) 615.
[51] M. Hajsadeghi, F.J. Alaee, A. Shahmohammadi, Investigation on behaviour of square/rectangular reinforced concrete columns retrofitted with FRP jacket, J. Civ. Eng. Manage. 17 (3) (2011) 400–408.
[52] J.G. Teng, FRP-strengthened RC structures, Wiley, 2002.
[53] Y.-F. Wu, T. Liu, D. Oehlers, Fundamental principles that govern retrofitting of reinforced concrete columns by steel and FRP jacketing, Adv. Struct. Eng. 9 (4) (2006) 507–533.
[54] L. Lam, J. Teng, Ultimate condition of fiber reinforced polymer-confined concrete, J. Compos. Constr. 8 (6) (2004) 539–548.
[55] A. Nanni, M.S. Norris, FRP jacketed concrete under flexure and combined flexure-compression, Constr. Build. Mater. 9 (5) (1995) 273–281.
[56] P. Rochette, P. Labossiere, Axial testing of rectangular column models confined with composites, J. Compos. Constr. 4 (3) (2000) 129–136.
[57] ACI-Committee, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-08), American Concrete Institute, Farmington Hills, MI, 2008.
[58] T. Norris, H. Saadatmanesh, M.R. Ehsani, Shear and flexural strengthening of R/C beams with carbon fiber sheets, J. Struct. Eng. 123 (7) (1997) 903–911.
[59] P. Alagusundaramoorthy, I. Harik, C. Choo, Flexural behavior of R/C beams strengthened with carbon fiber reinforced polymer sheets or fabric, J. Compos. Constr. 7 (4) (2003) 292–301.
[60] S.A. Taleb, A.S. Salem, Bending and Shear Behavior of a Composite Beam Strengthened and Double-Confined with FRP-Jacket, Procedia Eng. 114 (2015) 165–172.
[61] Z.C. Tetta, L.N. Koutas, D.A. Bournas, Textile-reinforced mortar (TRM) versus fiber-reinforced polymers (FRP) in shear strengthening of concrete beams, Compos. B Eng. 77 (2015) 338–348.
[62] F. Ribeiro, J. Sena-Cruz, F.G. Branco, E. Júlio, Hybrid FRP jacketing for enhanced confinement of circular concrete columns in compression, Constr. Build. Mater. 184 (2018) 681–704.
[63] M. Saafi, E. Asa, Extending the service life of electric distribution and transmission wooden poles using a wet layup FRP composite strengthening system, J. Perform. Constr. Facil 24 (4) (2010) 409–416.
[64] A.C. Manalo, W. Karunasena, C. Sirimanna, G.B. Maranan, Investigation into fibre composites jacket with an innovative joining system, Constr. Build. Mater. 65 (2014) 270–281.
[65] W. Ferdous, Y. Bai, T.D. Ngo, A. Manalo, P. Mendis, New advancements, challenges and opportunities of multi-storey modular buildings–A state-of-the-art review, Eng. Struct. 183 (2019) 883–893.
[66] J. Williams, F.R.P. Pile, Jacket Solution has no 'Pier' in Timber, Pile Restoration (2009).
[67] M. Ehsani, FRP super laminates present unparalleled solutions to old problems, Reinf. Plast. 53 (6) (2009) 40–45.
[68] A. Beddiar, R. Zitoune, F. Collombet, Y. Grunevald, M. Abadlia, N. Bourahla, Compressive behaviour of concrete elements confined with GFRP-prefabricated bonded shells, Eur. J. Environ. Civ. Eng. 19 (1) (2015) 65–80.
[69] H. Karagah, M. Dawood, A. Belarbi, Experimental study of full-scale corroded steel bridge piles repaired underwater with grout-filled fiber-reinforced polymer jackets, J. Compos. Constr. 22 (3) (2018) 04018008.
[70] G. Van Erp, C. Cattell, T. Heldt, Fibre composite structures in Australia's civil engineering market: an anatomy of innovation, Prog. Struct. Mat. Eng. 7 (3) (2005) 150–160.
[71] Strong-Tie, FX-70 Structural Piling Repair and Protection System https://www.strongtie.com/products/rps/fx70 2013 2018)
[72] Five Star, Five Star PileForm fiberglass reinforced plastic pile rehabilitation jackets, 2016. https://www.fivestarproducts.com/pileform-f-jacket.html.
[73] FiberSystems, FiberSystems supplies composite pile jackets, Reinforced Plastics 61(2) (2017) 65.
[74] L.C. Hollaway, A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties, Constr. Build. Mater. 24 (12) (2010) 2419–2445.
[75] J.R. Davis, Corrosion: Understanding the basics, Asm Int. (2000).
[76] P.K. Mehta, Durability of concrete in marine environment–A review, Spec. Publ. 65 (1980) 1–20.
[77] M. Safehian, A.A. Ramezanianpour, Assessment of service life models for determination of chloride penetration into silica fume concrete in the severe marine environmental condition, Constr. Build. Mater. 48 (2013) 287–294.
[78] S. Tang, Z. Li, E. Chen, H. Shao, Non-steady state migration of chloride ions in cement pastes at early age, RSC Adv. 4 (89) (2014) 48582–48589.
[79] Z. Li, Advanced Concrete Technology, John Wiley & Sons, 2011.
[80] J.G. Castaño, C.A. Botero, A.H. Restrepo, E.A. Agudelo, E. Correa, F. Echeverría, Atmospheric corrosion of carbon steel in Colombia, Corros. Sci. 52 (1) (2010) 216–223.
[81] X. Liu, A. Nanni, P.F. Silva, R.A. Laboube, Rehabilitation of steel bridge columns with FRP composite materials, Proc. CCC (2001) 10–12.
[82] H. Grube, W. Rechenberg, Durability of concrete structures in acidic water, Cem. Concr. Res. 19 (5) (1989) 783–792.
[83] U. Schneider, W. Piasta, The behaviour of concrete under Na2 S04 solution attack and sustained compression or bending, Mag. Concr. Res. 43 (157) (1991) 281–289.
[84] M.T. Bassuoni, M.L. Nehdi, Durability of self-consolidating concrete to sulfate attack under combined cyclic environments and flexural loading, Cem. Concr. Res. 39 (3) (2009) 206–226.
[85] . Ju, L. Weng, S. Mindess, A. Boyd, Damage assessment and service life prediction of concrete subject to sulfate attack, Materials Science of Concrete: Sulfate Attack Mechanisms (1999).
[86] S.A. Mangi, M.H. Wan Ibrahim, N. Jamaluddin, M.F. Arshad, R. Putra Jaya, Short-term effects of sulphate and chloride on the concrete containing coal bottom ash as supplementary cementitious material, Eng. Sci. Technol. Int. J. 22 (2) (2019) 515–522.
[87] M.W. Montgomery Repair and replacement of acid-damaged piles, International Conference on Case Histories in Geotechnical Engineering., St 1984 Louis, Missouri
[88] B. Mather, Concrete durability, Cem. Concr. Compos. 26 (1) (2004) 3–4.
[89] J.G. Cabrera, Deterioration of concrete due to reinforcement steel corrosion, Cem. Concr. Compos. 18 (1) (1996) 47–59.
[90] C. Lee, J. Bonacci, M.D. Thomas, M. Maalej, S. Khajehpour, N. Hearn, S. Pantazopoulou, S. Sheikh, Accelerated corrosion and repair of reinforced concrete columns using carbon fibre reinforced polymer sheets, Can. J. Civ. Eng. 27 (5) (2000) 941–948.
[91] C. Fang, K. Lundgren, L. Chen, C. Zhu, Corrosion influence on bond in reinforced concrete, Cem. Concr. Res. 34 (11) (2004) 2159–2167.
[92] T. El Maaddawy, A. Chahrour, K. Soudki, Effect of fiber-reinforced polymer wraps on corrosion activity and concrete cracking in chloride-contaminated concrete cylinders, J. Compos. Constr. 10 (2) (2006) 139–147.
[93] Y. Du, L.A. Clark, A.H. Chan, Impact of reinforcement corrosion on ductile behavior of reinforced concrete beams, ACI Struct. J. 104 (3) (2007) 285.
[94] A.A. Torres-Acosta, S. Navarro-Gutierrez, J. Terán-Guillén, Residual flexure capacity of corroded reinforced concrete beams, Eng. Struct. 29 (6) (2007) 1145–1152.
[95] J. Rodriguez, L. Ortega, J. Casal, Load carrying capacity of concrete structures with corroded reinforcement, Constr. Build. Mater. 11 (4) (1997) 239–248.
[96] D.V. Val, Deterioration of strength of RC beams due to corrosion and its influence on beam reliability, J. Struct. Eng. 133 (9) (2007) 1297–1306.
[97] A.C. Manalo, A.A. Mohammed, G.B. Maranan, Novel Composites Jacket for Repair of Concrete Structures, Proceedings of the 13th Fiber Reinforced Polymer for Reinforced Concrete Structures (FRPRCS13), Anaheim, California, United States of America, 2017.
[98] J. Cairns, Z. Zhao, Behaviour of concrete beams with exposed reinforcement, Proceedings of the Institution of Civil Engineers: Structures and Bridges, 1993.
[99] M. Harajli, Bond stress–slip model for steel bars in unconfined or steel FRC, or FRP confined concrete under cyclic loading, J. Struct. Eng. 135 (5) (2009) 509–518.
[100] R.-Y. Wu, C.P. Pantelides, Concentrated and distributed plasticity models for seismic repair of damaged RC bridge columns, J. Compos. Constr. 22 (5) (2018) 04018044.
[101] L.-V. Beaulieu, F. Legeron, S. Langlois, Compression strength of corroded steel angle members, J. Constr. Steel Res. 66 (11) (2010) 1366–1373.
[102] U.S. Army, U.S. Navy, U.S. Air Force, Chapter 2: Timber structures, Maintenance of Waterfront Facilities1978.
[103] B. Pizzo, N. Macchioni, C. Capretti, E. Pecoraro, L. Sozzi, L. Fiorentino, Assessing the wood compressive strength in pile foundations in relation to diagnostic analysis: The example of the Church of Santa Maria Maggiore, Venice, Constr. Build. Mater. 114 (2016) 470–480.
[104] R.K. Klaassen, Bacterial decay in wooden foundation piles—Patterns and causes: A study of historical pile foundations in the Netherlands, Int. Biodeterior. Biodegrad. 61 (1) (2008) 45–60.
[105] A.P. Schniewind, Physical and mechanical properties of archaeological wood, Physical and mechanical properties of archaeological wood. (225) (1990) 87-109.
[106] T. Ozbakkaloglu, Compressive behavior of concrete-filled FRP tube columns: Assessment of critical column parameters, Eng. Struct. 51 (2013) 188–199.
[107] J. Berthet, E. Ferrier, P. Hamelin, Compressive behavior of concrete externally confined by composite jackets. Part A: experimental study, Constr. Build. Mater. 19 (3) (2005) 223–232.
[108] G. Li, S. Kidane, S.-S. Pang, J. Helms, M.A. Stubblefield, Investigation into FRP repaired RC columns, Compos. Struct. 62 (1) (2003) 83–89.

[109] A. Parvin, A.S. Jamwal, Performance of externally FRP reinforced columns for changes in angle and thickness of the wrap and concrete strength, Compos. Struct. 73 (4) (2006) 451–457.

[110] J.C. Lim, T. Ozbakkaloglu, Hoop strains in FRP-confined concrete columns: experimental observations, Mater. Struct. 48 (9) (2015) 2839–2854.

[111] S.T. Smith, S.J. Kim, H. Zhang, Behavior and effectiveness of FRP wrap in the confinement of large concrete cylinders, J. Compos. Constr. 14 (5) (2010) 573–582.

[112] A.Z. Fam, S.H. Rizkalla, Confinement model for axially loaded concrete confined by circular fiber-reinforced polymer tubes, Struct. J. 98 (4) (2001) 451–461.

[113] J.G. Teng, T. Yu, D. Fernando, Strengthening of steel structures with fiber-reinforced polymer composites, J. Constr. Steel Res. 78 (2012) 131–143.

[114] VicRoads, Code of Practice: FRP for strengthening of bridge structures, in: V. Roads (Ed.) 2018.

[115] A. Fam, S. Rizkalla, Behavior of axially loaded concrete-filled circular FRP tubes, ACI Struct. J. 98 (3) (2001) 280–289.

[116] W.-K. Hong, H.-C. Kim, Behavior of concrete columns confined by carbon composite tubes, Can. J. Civ. Eng. 31 (2) (2004) 178–188.

[117] H. Kim, K.H. Lee, Y.H. Lee, J. Lee, Axial behavior of concrete-filled carbon fiber-reinforced polymer composite columns, Struct. Des. Tall Spec. Build. 21 (3) (2012) 178–193.

[118] T. Vincent, T. Ozbakkaloglu, Influence of fiber orientation and specimen end condition on axial compressive behavior of FRP-confined concrete, Constr. Build. Mater. 47 (2013) 814–826.

[119] M.R. Bambach, H.H. Jama, M. Elchalakani, Axial capacity and design of thin-walled steel SHS strengthened with CFRP, Thin-Walled Struct. 47 (10) (2009) 1112–1121.

[120] L. Lam, J. Teng, Design-oriented stress–strain model for FRP-confined concrete, Constr. Build. Mater. 17 (6) (2003) 471–489.

[121] Simpson Strong-Tie, FX-70® Structural Piling Repair and Protection System, 2018. https://www.strongtie.com/products/rps/fx70.

[122] A.A. Mohammed, A.C. Manalo, G.B. Maranan, Y. Zhuge, P.V. Vijay, Comparative study on the behaviour of different infill materials for pre-fabricated fibre composite repair systems, Constr. Build. Mater. 172 (2018) 770–780.

[123] M. Shamsuddoha, M.M. Islam, T. Aravinthan, A. Manalo, K.-T. Lau, Characterisation of mechanical and thermal properties of epoxy grouts for composite repair of steel pipelines, Mater. Des. 52 (2013) 315–327.

[124] M. Shamsuddoha, Behaviour of Infilled Rehabilitation System with Composites for Steel Pipe, University of Southern Queensland, 2014.

[125] W. Sum, K. Leong, Numerical study of annular flaws/defects affecting the integrity of grouted composite sleeve repairs on pipelines 0731684413503721, J. Reinf. Plast. Compos. (2013).

[126] A. Deb, S. Bhattacharyya, Investigation into the effect of bonding on FRP-wrapped cylindrical concrete columns, J. Compos. Constr. 14 (6) (2010) 706–719.

[127] H. Saadatmanesh, M. Ehsani, L. Jin, Seismic retrofitting of rectangular bridge columns with composite straps, Earthquake Spectra 13 (2) (1997) 281–304.

[128] Z. Yan, C.P. Pantelides, Concrete column shape modification with FRP shells and expansive cement concrete, Constr. Build. Mater. 25 (1) (2011) 396–405.

[129] Z. Yan, C.P. Pantelides, L.D. Reaveley, Posttensioned FRP composite shells for concrete confinement, J. Compos. Constr. 11 (1) (2007) 81–90.

[130] T. Ozbakkaloglu, J.C. Lim, T. Vincent, FRP-confined concrete in circular sections: Review and assessment of stress–strain models, Eng. Struct. 49 (2013) 1068–1088.

[131] D.A. Moran, C.P. Pantelides, Elliptical and circular FRP-confined concrete sections: A Mohr-Coulomb analytical model, Int. J. Solids Struct. 49 (6) (2012) 881–898.

[132] D.A. Moran, C.P. Pantelides, L.D. Reaveley, Mohr-coulomb model for rectangular and square FRP-confined concrete, Compos. Struct. 209 (2019) 889–904.

[133] Y. Xiao, H. Wu, Compressive behavior of concrete confined by carbon fiber composite jackets, J. Mater. Civ. Eng. 12 (2) (2000) 139–146.

[134] L. Lam, J. Teng, Strength models for fiber-reinforced plastic-confined concrete, J. Struct. Eng. 128 (5) (2002) 612–623.

[135] J. Berthet, E. Ferrier, P. Hamelin, Compressive behavior of concrete externally confined by composite jackets: Part B: Modeling, Constr. Build. Mater. 20 (5) (2006) 338–347.

[136] Z. Yan, C. Pantelides, Design-oriented model for concrete columns confined with bonded FRP jackets or post-tensioned FRP shells, Proceedings of the 8th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures, University of Patras, 2007.

[137] J. Teng, T. Jiang, L. Lam, Y. Luo, Refinement of a design-oriented stress–strain model for FRP-confined concrete, J. Compos. Constr. 13 (4) (2009) 269–278.

[138] H.-L. Wu, Y.-F. Wang, L. Yu, X.-R. Li, Experimental and computational studies on high-strength concrete circular columns confined by aramid fiber-reinforced polymer sheets, J. Compos. Constr. 13 (2) (2009) 125–134.

[139] M.F. Fahmy, Z. Wu, Evaluating and proposing models of circular concrete columns confined with different FRP composites, Compos. B Eng. 41 (3) (2010) 199–213.

[140] T. Yu, J. Teng, Design of concrete-filled FRP tubular columns: provisions in the Chinese technical code for infrastructure application of FRP composites, J. Compos. Constr. 15 (3) (2010) 451–461.

[141] J.C. Lim, T. Ozbakkaloglu, Confinement model for FRP-confined high-strength concrete, J. Compos. Constr. 18 (4) (2013) 04013058.

[142] G. Lin, T. Yu, J. Teng, Design-Oriented Stress-Strain Model for Concrete under Combined FRP-Steel Confinement 04015084, J. Compos. Constr. (2015).

[143] M.R. Spoelstra, G. Monti, FRP-confined concrete model, J. Compos. Constr. 3 (3) (1999) 143–150.

[144] A. Mirmiran, M. Shahawy, Behavior of concrete columns confined by fiber composites, J. Struct. Eng. 123 (5) (1997) 583–590.

[145] S.P.C. Marques, D.C.D.S.C. Marques, J. Lins da Silva, M.A.A. Cavalcante, Model for analysis of short columns of concrete confined by fiber-reinforced polymer, J. Compos. Constr. 8 (4) (2004) 332–340.

[146] D.A. Moran, C.P. Pantelides, Stress-strain model for fiber-reinforced polymer-confined concrete, J. Compos. Constr. 6 (4) (2002) 233–240.

[147] B. Binici, An analytical model for stress–strain behavior of confined concrete, Eng. Struct. 27 (7) (2005) 1040–1051.

[148] T. Jiang, J. Teng, Analysis-oriented stress–strain models for FRP–confined concrete, Eng. Struct. 29 (11) (2007) 2968–2986.

[149] C. Aire, R. Gettu, J. Casas, S. Marques, D. Marques, Concrete laterally confined with fibre-reinforced polymers (FRP): experimental study and theoretical model, Materiales de Construcción 60 (297) (2010) 19–31.

[150] Q. Xiao, J. Teng, T. Yu, Behavior and modeling of confined high-strength concrete, J. Compos. Constr. 14 (3) (2010) 249–259.

[151] J. Teng, G. Lin, T. Yu, Analysis-oriented stress-strain model for concrete under combined FRP-steel confinement, J. Compos. Constr. 19 (5) (2014) 04014084.

[152] O. Chaallal, M. Shahawy, M. Hassan, Performance of axially loaded short rectangular columns strengthened with carbon fiber-reinforced polymer wrapping, J. Compos. Constr. 7 (3) (2003) 200–208.

[153] T.M. Pham, M.N. Hadi, J. Youssef, Optimized FRP wrapping schemes for circular concrete columns under axial compression, J. Compos. Constr. 19 (6) (2015) 04015015.

[154] T. Turgay, Z. Polat, H. Koksal, B. Doran, C. Karakoç, Compressive behavior of large-scale square reinforced concrete columns confined with carbon fiber reinforced polymer jackets, Mater. Des. 31 (1) (2010) 357–364.

[155] T.E. Maaddawy, Strengthening of eccentrically loaded reinforced concrete columns with fiber-reinforced polymer wrapping system: experimental investigation and analytical modeling, J. Compos. Constr. 13 (1) (2009) 13–24.

[156] F. Colomb, H. Tobbi, E. Ferrier, P. Hamelin, Seismic retrofit of reinforced concrete short columns by CFRP materials, Compos. Struct. 82 (4) (2008) 475–487.

[157] J.-J. Zeng, Y.-C. Guo, W.-Y. Gao, W.-P. Chen, L.-J. Li, Stress-strain behavior of concrete in circular concrete columns partially wrapped with FRP strips, Compos. Struct. 200 (2018) 810–828.

[158] J.B. Mander, M.J.N. Priestley, R. Park, Theoretical Stress-Strain Model for Confined Concrete, J. Struct. Eng. 114 (8) (1988) 1804–1826.

[159] H. Saadatmanesh, M.R. Ehsani, M.-W. Li, Strength and ductility of concrete columns externally reinforced with fiber composite straps, Struct. J. 91 (4) (1994) 434–447.

[160] T.M. Pham, J. Youssed, M.N. Hadi, T.M. Tran, Effect of different FRP wrapping arrangements on the confinement mechanism, Procedia Eng. 142 (2016) 306–312.

[161] A.A. Mohammed, A.C. Manalo, G.B. Maranan, Y. Zhuge, P. Vijay, J. Pettigrew, Behavior of damaged concrete columns repaired with novel FRP jacket, J. Compos. Constr. 23 (3) (2019) 04019013.

[162] T.V. Parry, S. Wronski, Selective reinforcement of an aluminium alloy by adhesive bonding with uniaxially aligned carbon fibre/epoxy composites, Composites 12 (4) (1981) 249–255.

[163] M. Tavakkolizadeh, H. Saadatmanesh, Fatigue Strength of Steel Girders Strengthened with Carbon Fiber Reinforced Polymer Patch, J. Struct. Eng. 129 (2) (2003) 186–196.

[164] A. Shaat, A. Fam, Fiber-Element Model for Slender HSS Columns Retrofitted with Bonded High-Modulus Composites, J. Struct. Eng. 133 (1) (2007) 85–95.

[165] M.R. Bambach, M. Elchalakani, Plastic mechanism analysis of steel SHS strengthened with CFRP under large axial deformation, Thin-Walled Struct. 45 (2) (2007) 159–170.

[166] J. Solan, USQ, Joinlox collaborate on prefabricated composite repair system, Composites World, 2017.