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ABSTRACT

This paper presents a concise state-of-the-art review on the use of Fiber Reinforced Polymers (FRPs) in bridge engineering. The paper is organized into commonly used FRP bridge components, and different materials/manufacturing techniques used for repairing and construction of FRP bridges. Efforts have been made to give a clear and concise view of FRP bridges using the most relevant literature. FRPs have certain desired properties like high strength to weight ratio, and high corrosion and fatigue resistance that make them a sustainable solution for bridges. However, as FRPs are brittle and susceptible to damage, when safety is concerned, critical parts of the bridges are made as hybrids of FRP and conventional materials. Despite significant studies, it has been found that a comprehensive effort is still required on better understanding the long term performance and end-of-life recycling, developing cost-effective and flexible manufacturing processes such as 3D printing, and developing green composites to take full advantages of FRPs.

1. Introduction

Fiber Reinforced Polymers (FRPs) have excellent properties such as high strength, light weight, and corrosion resistance. These materials have been widely used in many industrial sectors such as automotive, marine, aerospace, train, sport and wind [1]. Over 20% of produced FRPs are applied in civil and construction industry globally [2,3] with FRP bridges being one of the popular applications [4,5]. FRPs have been widely used to repair deteriorated bridges and to retrofit conventional concrete bridges that do not meet updated code requirements [6]. More specifically, they are used mostly for replacing the degraded concrete decks in steel-concrete bridges that are subjected to corrosion during their service life [6]. In addition, FRPs are applied to retrofit bridges' columns and piers [7]. These materials improve the seismic axial and lateral load capacity, resulting in less shear failure, flexural plastic hinge failure and lap splice failure [8]. This is because FRPs can be designed to provide a wide range of tensile, flexural, impact, and compressive strengths [9]. Furthermore, there are successful projects in which FRPs serve for aesthetic purposes such as a cladding material around decks as well as load-bearing shell and folding structures [10]. As an example, Fig. 1 shows a fly-over Waarderpolder bridge in Netherland with FRP edge elements completed in 2013 [10].

A book published in 2014 reviews the use of advanced composites in the design and construction of bridges, including damage identification and the use of large rupture strain FRP composites [6]. Many different case studies have been discussed and detailed in the book, but it does not provide a comprehensive view on how FRPs are used in different bridge components, their advantages and disadvantages and their affordability. Besides, most of the published review papers on FRP bridges are focused mainly on a special component such as decks [11] and tendons [12,13]. There are also other review papers that are related to FRP bridges in a specific country such as the US [14,15], the UK [16], and Netherland [10], and the majority of their cited papers were published before 2014.

Therefore, little knowledge is provided in the literature on global recent developments in FRP bridges. From the literature review and to the author's best knowledge, there is no comprehensive and concise review paper to summarise related activities of FRP bridges from the start up to recent time. This review paper is therefore presented to fill

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such gap by summarising most activities in the literature on: i) history of FRP bridges, ii) advantages and disadvantages of FRP bridges, iii) classification of different parts of bridges made from FRPs, and iv) their material properties and manufacturing methods.

2. History of FRP bridges

Table 1 shows several pioneer countries in the field of FRP bridges in chronological order. Although it is difficult to say who made the first FRP bridge [17], many researchers have reported that the first FRP pedestrian bridge was made in 1975 by the Israelis [6,18–20]. It was then followed by Aberfeldy footbridge [21] that was completed in 1992 as the world's first major advanced FRP footbridge in the UK. This was rapidly followed by the Bonds Mill Lifting bridge [17] in the UK in 1995, which was the first road bridge entirely made from FRP.

Researches on using FRPs in bridges in the US started in the late 1980s [14]. The first FRP bridge in the US was built in 1994, which was designed by Lochheed Martin [18,25]. Around 300 FRP pedestrian and 50 highway bridges with FRPs in the US were reported in 2005 [14]. More than 500 FRP bridges were reported across the North America from 1997 to 2017 [26]. In other European countries such as Denmark, Netherland and Norway, FRPs have been used for over 20 years in the bridge industry and over 600 FRP bridges are reported by 2018 [17,23,27]. Canada started the research on steel free deck using FRP bars in 1995 [24]. In 2000, the Canadian Highway Bridge Design Code introduced these bars as reinforcement for concrete slabs, girders, and barrier walls of bridges. In 2004 glass FRP bars were used to reinforce Cookshire-Eaton Bridge' deck as the first FRP bridge in Canada [28,29]. Korea started its research on FRP decks in the early 2000s and completed an FRP deck with steel girders in 2001 and built a complete FRP bridge in 2002 in South Korea [24]. In Japan, Okinawa Road Park Bridge was the first FRP pedestrian bridge which was erected in 2000; before this, FRP bridges were used for experiments and trial models [30,31]. China started the research on glass FRP bridges since the 1970s, constructed a glass FRP bridge deck in 1982. Since then China has witnessed the continuous application of FRPs in bridges [22].

3. Advantage and disadvantages of FRP bridges

FRPs are making a breakthrough in bridges and are increasingly being used in different parts of bridges to repair, improve the performance, reduce weight, and save time and money. Nowadays sustainability is a new way of thinking in the construction of structures [32]. Current bridges should meet sustainable environmental, social, and economic requirements [33]. Fig. 2 shows a concise view of the advantageous sustainable factors of FRP bridges.

Table 1
Several pioneer countries in using FRP bridges.

Name of the bridge		Year	Bridge type
Israel [18]	–	1975	Footbridge
China [22]	Miyun	1982	Vehicle Bridge
UK [21]	Aberfeldy	1992	Footbridge
US [18]	–	1994	Vehicle Bridge
Denmark [23]	Kolding	1997	Vehicle Bridge
Netherland [20]	Harlingen	1997	Footbridge
South Korea [24]	Beoncheon	2001	Vehicle Bridge
Norway [17]	Fredrikstad	2003	Vehicle Bridge

While steel bridges have up to 50 years lifespan, FRP bridges are expected to last 100 years [34]. In addition, the average weight of an FRP bridge is about half the weight of a steel bridge, and it is five times lighter than its concrete equivalent with the same performance [10]. For example, Mapledurham bridge's FRP deck in the UK with five tonnes and Komagari dam's FRP gates in Japan with 248 kg both weigh- a third of their conventional steel/concrete equivalent [30]. Having a lighter structure means minimizing the time of construction process [2,5,33,35], quick and easy installation, transporting and storage [7], fewer costs on substructure's material [36], and less needed labors [37,38], compared to the conventional bridges. FRPs can be prefabricated, so it is possible to install bridges during off-traffic times with minimum traffic disruption [39] and on-site construction time [40]. Besides, CO_2 emission reduction due to reduced fuel for transportation and reduction of traffic congestion due to the faster installation of the bridge [41] CO_2 emission during FRP production is higher than those during conventional steel and concrete productions [42]. These matters result in a less negative impact on users and society, especially in the areas with intensive vehicle traffic and pollution such as highways [33]. A case study illustrated that bridges with spans up to 40 feet long usually can be built in less than a day by as few as three workers [9]. For example, an FRP deck at No-Name Creek in the US and FRP girders of a bridge in Madrid along the M111 freeway were completed in just 10 and 3 h, respectively [43,44]. The latter was manufactured in Madrid and then transported on a truck to the worksite, located in the north of Spain.

Life cycle cost (LCC) is a factor for calculating bridges' overall costs. LCC consists of initial, maintenance/inspection, and repair/rehabilitation costs. It has been demonstrated that the cost of producing FRP structure is over 50% more than the steel and prestressed concrete alternative structures [30]. In addition, FRP production requires a very

Fig. 1. Fly-over Waarderpolder bridge in Netherland with FRP edge elements [10]. A single column fitting image.

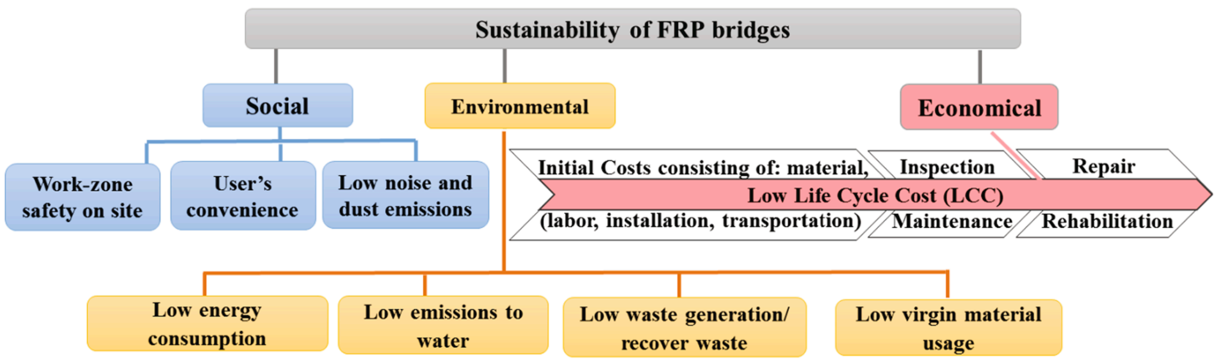

Fig. 2. Sustainability of FRP bridges. A 2-column fitting image.

large amount of energy, compared to those of other conventional materials [42]. However, LCCs of FRPs may be less than conventional concrete/steel/timber bridges due to lower repairing and manufacturing costs [7,45–47]. LCC is a challenging discussion on FRP bridges. Although it is reported that the FRP technology is economical for special parts such as bridge deck construction and repair, it is not yet clear whether FRPs are cost-competitive for standard short-span bridges or not [47]. There is a study on the economical behavior of long-span cable-stayed bridges, with different types of components made of carbon FRP [18]. The study proved that in comparison with conventional bridges, the total cost of a long span bridge with carbon FRP components could be effective in the near future for all the case studies listed in Table 2, when the cost ratio of carbon FRP to steel is smaller than 16/1 as shown in Fig. 3.

Fig. 4-a shows a schematic of the predicted LCC savings of FRP bridges according to a report by Fiber-Core Europe [48]. Fig. 4-b shows sample case studies comparing initial, maintenance, and LCCs associated with FRP bridges compared with conventional equivalent bridges in Japan. Considering Fig. 4-b, the initial cost of the FRP bridges are higher than their equivalent conventional bridges, while due to their lower LCCs, the FRP bridges have a competitive edge and are more efficient when longer life is required in severely corrosive environments. FRP bridges are highly resistant to almost all known aggressive chemicals and they just need regular cleaning to be functional [10]. This results in a longer service life compared with conventional bridges that require further maintenance, repair, repainting, and replacement [48].

FRPs do not conduct electricity, so they could be used for being safe in endangering areas such as over the railway traction and bridges in factories to prevent from electric shock. These materials also make bridges resistant to de-icing salts in cold periods. However, FRPs lack in fire resistance and this may result in higher works to cover them with fire resistant materials if it is necessary [49].

Despite fatigue resistance of FRPs compared with mild steel and a few other alloys [49], FRPs are quite brittle and susceptible to different damage mechanisms (Fig. 5-a) [50] under different loadings, with little damage visibility and catastrophic failure after the damage. Thus, a main concern about the FRP bridges is damage of the FRP bridge deck [51]. Whereas metallic materials such as steel are behaving in a ductile manner and are more damage tolerant [52] as shown in Fig. 5-b.

Table 2
Definition of the six types of the proposed cable-stayed bridges of Ref [18]. *CFRP = Carbon FRP.

Type	Girder	Bridge deck	Stay cables	Pylons
I	Steel	Steel	Steel	Concrete
II	Steel	Steel	Composite	Concrete
III	Steel	Steel	CFRP	Concrete
IV	Steel	CFRP	Steel	Concrete
V	Steel	CFRP	Composite	Concrete
VI	Steel	CFRP	CFRP	Concrete

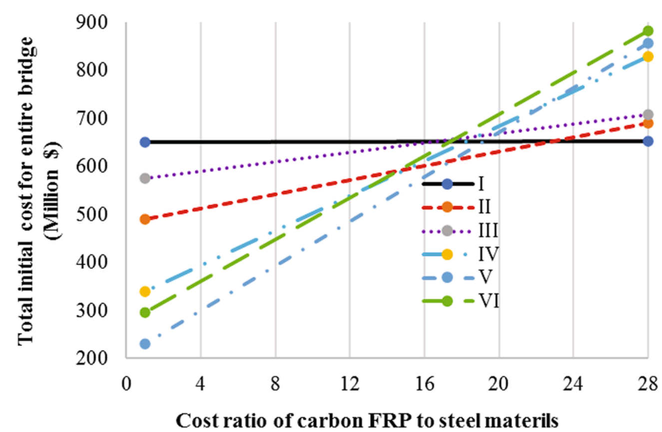

Fig. 3. Total cost for the entire bridge versus cost ratio of carbon FRP to steel [18]. A single column fitting image.

Furthermore, fatigue loading even at low ranges could be detrimental for the stress transfer between the FRP and concrete [6]. Therefore, sometimes when safety is concerned, critical parts of the bridges such as connections may have reliabilities over 6 or 7 [32], or are used as hybrids of FRP and conventional materials such as steel reinforced concrete to take advantages of both material systems [54]. Overall, the fatigue resistance of bonded and bolted connections may control the life of the FRP bridges [49].

FRP bridges also lack in thermal compatibility between concrete and FRP compared to steel-reinforced bridges [55]. FRPs are also exposed to water absorption degradation when subjected to the concrete pore water solution (as an alkaline solution), which decreases their mechanical properties such as elastic modulus, tensile, shear, and bond strengths significantly [6]. Besides, there is hesitation in taking the full advantage of FRPs due to the absence of code of practice, standards, guidelines for design and detailing, and lack of clear understanding of their structural performance and life assessment under short-term and long-term loads [7].

4. Classification of different parts of bridges made from FRPs

Based on the traffic type, there are 3 types of pedestrian, vehicle, and railway bridges [9,14]. Overall, components of all bridges are mainly classified as substructures and superstructures as shown in Fig. 6. In the bridge industry, FRPs are mainly used to repair or strengthen the bridge's superstructure (mostly deck, girder, or beam), bridge's substructure (consisting of piles, pier's columns, pier's caps, and arches).

Fig. 7 shows the estimated proportions of FRP components in around 400 bridges all around the world. The data is extracted from the studies conducted in 2000 [54] and in 2003 [47], and case studies of

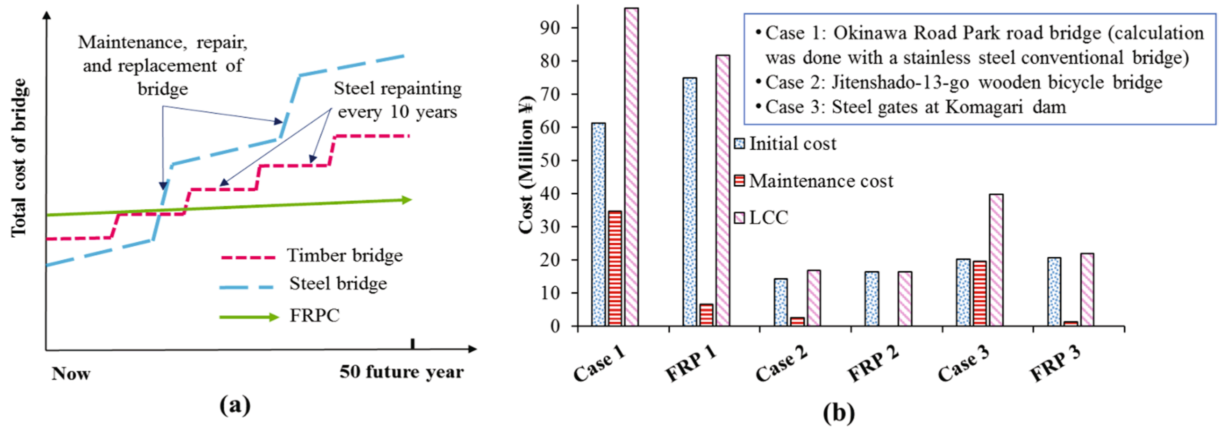

Fig. 4. (a) Schematic of LCC of different bridge types (FiberCore Europe) [48] and (b) comparing the initial, maintenance and LCCs of 3 conventional bridges with FRP substitutions (data are extracted from [30]). A 2-column fitting image.

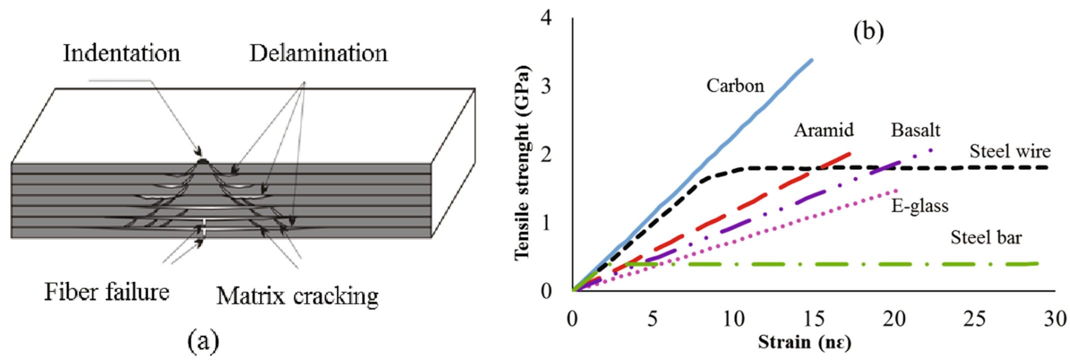

Fig. 5. a) damage mechanisms induced in laminated FRs under indentation [50] b) Comparison of stress–strain curves for some FRPs and a common steel part subjected to tension load [53]. A 1.5 column fitting image.

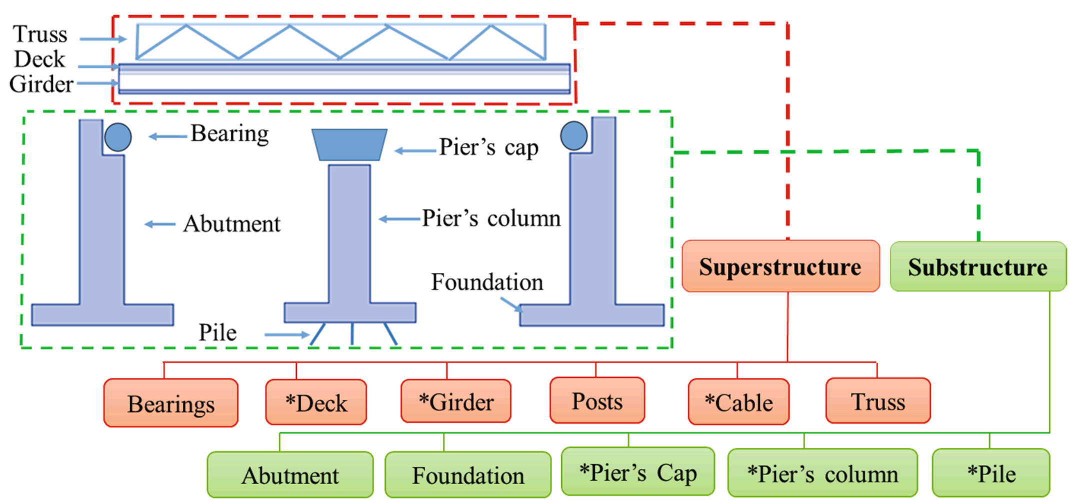

Fig. 6. Main parts of a bridge (* the most common FRP components). A 1.5 column fitting image.

Composites UK institute [56]. Around 14% of the bridges are completely built or replaced with FRP components, while about 75% of FRPs are used in superstructure components and just 8% of FRPs are used in substructures as shown in Fig. 7. The remaining 1% is accounted for other components such as truss or parapet that are considered as superstructure components.

For a better understanding, the most common applications of FRPs in different bridge components are summarised in Fig. 8. Table 3 reports different components manufactured or strengthened by FRPs in some of the UK's bridges.

4.1. *Superstructures*

4.1.1. *Deck*

FRP decks are the most popularly used structural elements in bridges [49]. Steel reinforced decks are in danger of corrosion due to de-icing

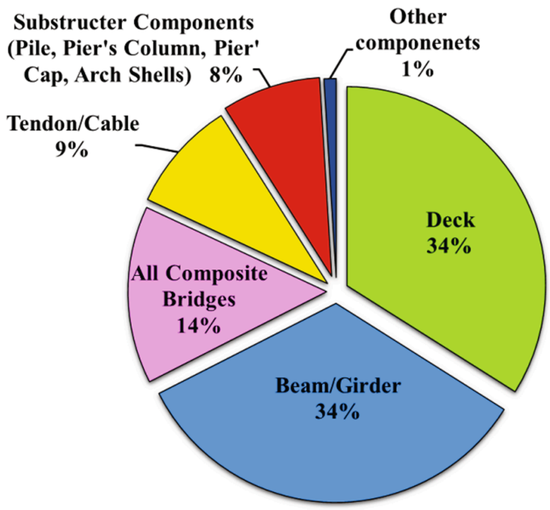

Fig. 7. FRP proportions in bridge components all around the world, extracted from over 400 bridges [4956–57]. A single column fitting image.

salts and other environmental issues, and consequently, they are in danger of failure due to stress concentration and increased traffic [6]. Concrete decks are typically predicted to last 25 years before requiring replacement while the lifespan of FRP decks is comfortably set at 75 years [60]. In addition to repairing and replacing, FRP has been implemented for widening and rehabilitation of the conventional steel reinforced decks [11,61].

FRPs have a high strength/stiffness per unit weight and they are corrosion resistant, therefore they are a good alternative to steel reinforcement for concrete bridge construction [55]. The reduction in self-weight provides lower stresses in the rest of the bridge and enables higher traffic loads carrying capacity. A study was simulated by applying 1 kN vertical point load on both conventional (chrome steel and aluminium) as well as glass FRP decks which were located on 7 beams as shown in Fig. 9-a [62]. As it is shown in Fig. 9-b and c, the reaction force proportions at the connections of the beams and stress distribution in the bottom flange of the central beam under the FRP deck are by far lower than the steel deck. This shows a higher load carrying capacity and lower weight of carbon FRP compared to steel decks.

There are two common types of FRP decks named sandwiched and adhesively bonded pultruded structures as shown in Fig. 8 [14,63]. The sandwiched decks have the FRP mass concentrated in the surface layers with low-density FRP cores. For the pultruded decks, continuous pultruded shapes are assembled into modular panels [64], and the required geometric shapes are usually manufactured using the pultrusion process [65].

An example of sandwiched FRP decks is the first deck rehabilitation project that was successfully completed by replacing a concrete deck with an FRP sandwiched deck in the US in 2000 [15]. Another example is a sandwiched deck with 15 mm E-glass/vinyl-ester surface skins and a beam shape web core composed of the same material with the empty places of the core filled with isocyanate foam blocks in 2000 [15]. As the replaced FRP deck weighs 80% less than the previous deck, it reduced the dead load and therefore increased the maximum live load capacity of the bridge. Steel grating of bascule Schuyler Heim Bridge is another example, where it failed earlier than the expected service life. As the bridge suffered from a localized failure of welded steel gratings due to the high fatigue and impact loads resulted from the heavy truck traffic. Therefore, the advantages of high fatigue resistance FRPs were used to remedy this problem [66]. The impact simulation results of the new deck showed that it exceeded the original steel deck's impact load carrying capacity by about 25%. Moreover, replacing the old steel deck of the Chemung County Bridge raised the operating capacity of the bridge from 33 to 61 tons [67].

Okinawa Road Park Bridge, Japan is another example in which pultruded glass FRP was used for the stiffeners, decks, and floor systems

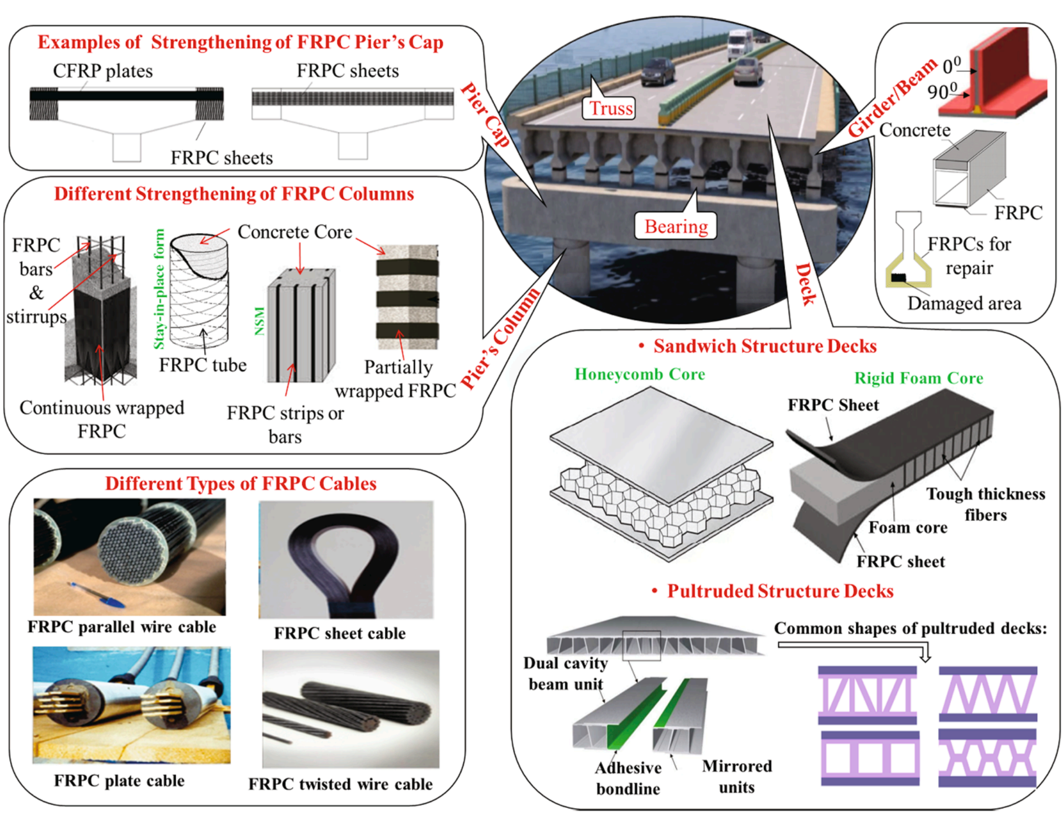

Fig. 8. The most common usage of FRPs in bridge industry. A 2-column fitting image.

Table 3
FRP components of the UK's FRP bridges [56–59].

FRP component type	Date	Bridge's name
Cables and deck	1991	Aberfeldy Footbridge
Complete bridge	1994	Bonds Mill Lift Bridge
Deck	1995	Parson's Footbridge
Deck and girder	2000–2001	Halgavor Bridge
Deck and beams	2002	West Mill Bridge
Deck	2006	Mount Pleasant Bridge
Complete bridge	2007	St Austell Railway Bridge
Deck, pier and trestles	2007	Launder Aqueduct
Deck	2007	Wilcott Bridge
Parapet replacement.	2008	Mort Lane Parapet
Complete bridge	2009	River Leri Footbridge
Superstructure replacement	2010	Staden Hay
Superstructure	2010	Bradkirk Footbridge
Bridge deck slabs	2010	Thompson's Bridge Deck Slabs
Deck replacement	2011	Calder & Rubha Gas Viaducts
Deck replacement	2011	Moss Canal Bridge
Complete replacement	2011	Dawlish Station Footbridge
Two bridge lifting decks	2012–2013	Dragon Bridge
Deck	2013	Purfleet Footbridge
Parapets	2014	FRP Parapets
Deck replacement	2014	Church Road Bridge
Aqueduct replacement	2014	River Chor Aqueduct
Deck planks	2014	Thornaby Footbridge
Deck	2015	Sedlescombe Bridge
Masonry stones replacement	2015	Bull Ring Farm Road Overbridge
Deck replacement	2016	Mapledurham Bridge
Deck replacement	2016	Bird Riding Footbridge
Complete replacement	2016–2017	East Row Footbridge
Complete bridge	2016–2019	Emersons Green East Cycle
Complete replacement	2017	Dover Sea Wall
Deck replacement	2017	Kiora Sluice Footbridge
Deck	2017	Prince Street Footbridge

in 2000 [68]. Neto and Rovere [69] also developed a footbridge deck system, which was consisted of a slab made of fiber reinforced concrete laid on glass FRP wide-flange pultruded profiles. This system sustained constructive and live pedestrian loads for footbridge deck applications.

4.1.2. Cables

Because of the advantages of FRPs such as high strength, lightweight, high corrosion resistance, excellent fatigue resistance, and lower thermal expansion, unidirectional FRP has great potential for cables and to replace steel cables in cable structures [70]. Density of the FRP cables is about 14%–40% of the traditional high-strength steel cables [71]. The possibility/feasibility of using FRP for very long-span bridges from 1000 to 10,000 m span length was verified, showing the potential to build bridges with main spans ranging up to 8400 m (across the Strait of Gibraltar), while steel cables are practically suitable for spans from 1000 to 1400 m [72–74]. An FRP cable is mainly composed of tendons (in the form of parallel wire strands or twisted wire strands), plates, or sheets as shown in Fig. 8.

In 1991, Kevlar-49 fibre cables were used in the world's first major advanced FRP footbridge (Aberfeldy, Scotland) [56]. After the early researches on cable-stayed bridges in many countries, three carbon FRP footbridges with full carbon FRP cables and two highway-bridges with partial carbon FRP cables were built between 1998 and 2005 in China, Denmark, Japan, Switzerland and United States [75]. The first carbon FRP cable-stayed bridge of 48.4 m length and 6.8 m width is located at the Jiangsu University, China [75].

Due to poor shear properties and anisotropic behavior, FRP cables are more sensitive to wind resistance, transverse pressure, and notch effects compared to steel cables [75]. As shown in Fig. 10, under an identical excitation load, the acceleration amplitude of a hybrid FRP cable is significantly larger than that of the high-strength steel cable indicating that FRP cables are more sensitive to external excitations. But designable characteristics of FRP cables make them flexible to improve the vibration stability [76,77]. If designed properly, FRP cables can improve cable-deck resonance and suppress the large amplitude vibrations of cables [71].

The existing studies on FRP cables include material properties, fatigue performance, vibration characteristics, creep behavior, durability, and damping properties [78,79]. A study showed that the displacements of an FRP cable-stayed bridges are less than those of the steel cable-stayed bridge [71]. Therefore, the use of FRP cables can increase the stiffness of cable-stayed bridges. This also results in decreasing the sag effect (vertical interval of the main cable in the main span) in FRP bridges. It was also shown that when the span of a cable-supported bridge reaches 1400 m, the sag of the CFRP cable is less than 17% of the steel cable as illustrated in Fig. 11 [77].

In 2015, a high-strength anchor system was introduced which was consisted of multi-tendon FRP cables. The winding of fiber roving around each tendon at the anchor zone benefits the integration of the tendons [81]. Tendons, consisting of 19 parallel basalt FRP, were manufactured with a nominal 4-mm diameter using unidirectional basalt fiber roving with 1200 tex and epoxy resin through pultrusion technology as shown in Fig. 12. The new anchor achieved a high anchor efficiency, with more than 100% improvement, and it can avoid any effects that may potentially weaken the strength of the FRP tendons in the cable.

4.1.3. Girders or beams

Several examples of FRPs for repair and manufacturing of girders are shown in Fig. 8. Compared with steel reinforcement, FRP reinforcement is linear elastic up to failure and, in general, it can develop much greater tensile strength than a steel reinforcement [82]. In 1997, pultruded glass/carbon hybrid FRP beams were used as superstructure in Tom's Creek Bridge in the US [83]. According to [84], the first FRP bridge repair in China was done on Miyun Bridge in 1982 with six hand lay-up glass FRP girders. The other cases are the girders of Okinawa Road Park bridge in Japan in 2000, two bridges over a motorway in 2007 in Madrid

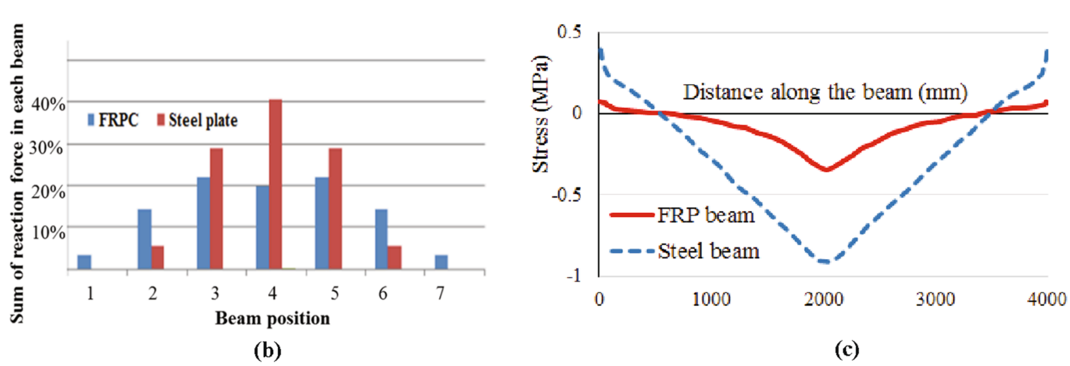

Fig. 9. (a) A bridge deck with 7 beams under 1 kN vertical load on beam 4, simulated (b) the proportion of the applied load that each beam carries, and (c) stress distribution along the span of the central beam under the steel and FRP decks [62]. A 1.5 column fitting image.

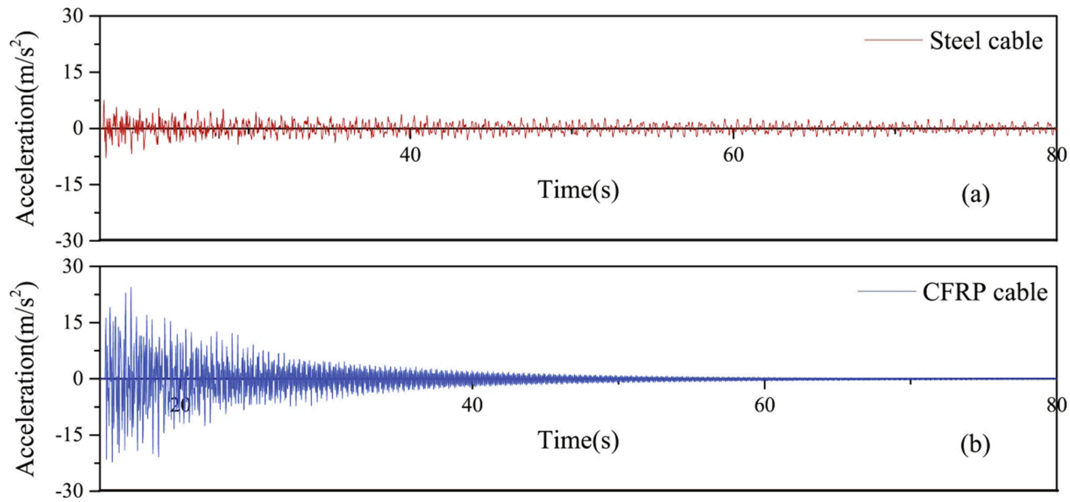

Fig. 10. Acceleration of steel cable and FRP cable under an identical load [71]. A single column fitting image.

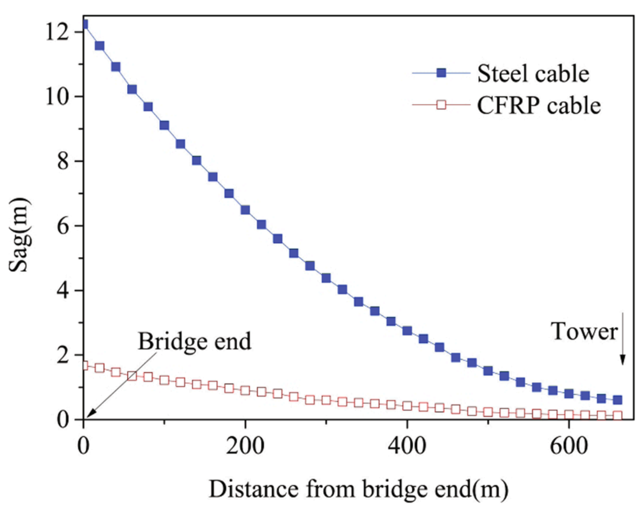

Fig. 11. Sag of a carbon FRP cable and a steel cable [80]. A single column fitting image.

(with extreme light weights of the girders, only 46 kN each) [43,85], and the first Polish FRP road bridge was built over the Ryjak river in 2015. Fig. 13 shows Com-bridge in Poland which consists of 4 glass/carbon FRP girders [86].

Mosallam [67] introduced the H-Lam, consisting of high strength FRP facing sheets bonded to a lightweight high density/high strength core material, as a new repairing system for steel components. H-lam method increased the strength of a steel beam from 15.4% to 27.5% compared to carbon FRP strips. This method was used for steel girders of a selected span of the Sauvie Island Bridge in the US.

In addition, hybrid girders are made in the form of concrete-filled FRP tubes (CFFT) [13,88–91] and stay-in-place (SIP) formworks [43]. Different shapes of FRP girders are shown in Fig. 14, which are mostly produced using pultrusion method. In 2018, researchers at the University of Maine, US have developed a 3D printed lightweight FRP bridge girder that is twice as strong as steel and concrete bridge girders [92].

4.2. Substructures

The role of FRP in substructures' repairing is twofold: first to restore lost flexural as well as shear load capacities due to steel corrosion; second to provide resistance to withstand expansive forces caused by corrosion of steel [36]. FRPs are also introduced to protect from bridges' abutments from potential impact by ships and barges [67]. A study showed that retrofitting of the arch stone bridge using FRPs can improve the seismic susceptibility by preventing the collapse of the stones [93]. The study consisted of repairing simulation of Saint Pont Martin bridge in Italy with fabricating the arch of the bridge using carbon FRPs. The results indicated that the load-carrying capacity as well as the flexural strength of the arch were increased using carbon FRPs. In addition, vertical displacement of the bridge's walls retrofitted using FRP decreased by 50%, which helps maintaining the structure of the bridge after an earthquake.

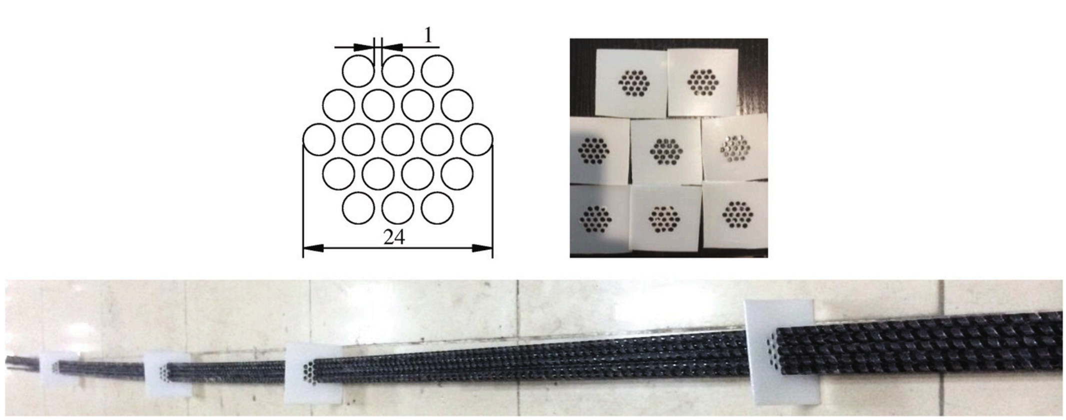

Fig. 12. Positioning and a cross sectional view of an FRP cable (units in mm) [81]. A single column fitting image.

Fig. 13. Application of FRP girders for Com-bridge in Poland [86,87]. A 1.5 column fitting image.

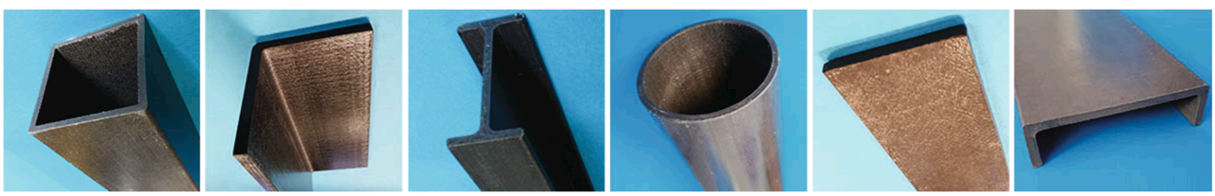

Fig. 14. Typical cross section forms of FRP girders. A 1.5 column fitting image.

In substructure's components, FRPs are usually used for the pier's column. A survey showed that carbon FRP-strengthening for up-grading bridge piers (primarily columns) is the most accepted standard practice, followed by glass FRP-reinforced bridge decks [94]. FRPs are also applied for repairing or strengthening the pier's cap. Transverse and longitudinal FRP reinforcement is done for increasing brittle shear failure and flexural failure respectively through the use of externally or internally reinforced FRP strips, stirrups, fabrics, or bars [95,96] (see Fig. 8). As shown in Fig. 8, the use of FRPs as an external reinforcement in pier's columns is done with; 1) wrapping FRP fabrics around the columns, 2) near-surface mounted (NSM) technique, i.e. placing FRP bars or strips into grooves pre-cut into the concrete, and 3) partially wrapping with FRP strips. The other efficient external use of FRPs is SIP form for concrete columns, as it eliminates the need for internal reinforcement and protects concrete against environmental effects [95]. FRP reinforcing bars and continuous stirrups were also used as internal flexural and/or shear reinforcements in concrete columns [54].

One of the oldest and longest wooden bridge' piles in the US is Powder Point Bridge which was repaired using glass FRP wrapping around the pile [97]. In the case of water crossings, corrosion is most severe at the splash zone. A total of 49 piles near the edges of four bridges in St. Louis (in the US) in I-70/I-270 interchange were severely corroded caused by polluted rain run-off as shown in Fig. 15 [98]. All the piles were repaired as with FRP wrapping (Fig. 15). Allen Creek, Gandy, and Friendship Trails Bridges in the US and Seomjin Bridge in South Korea are other examples of FRP wrapping to repair the bridges' piers and piles due to corrosion induced damage [36,99,100]. Table 4 lists the deteriorated bridges by 2000 in a number of states of the US which at least one part of their substructures was strengthen using FRP wrapping [101].

Fig. 15. One of the 49 corrosion damaged piles in I-70/I-270 Interchange (USA) that were repaired with wrapping FRP technique [98].

5. Materials and manufacturing methods of FRP bridges' components

According to [9,10,70], considering the material properties and costs in the bridge industry, orthophthalic polyester, isophthalic polyester, vinyl esters, and epoxies are the most commonly used thermoset resins, respectively. While water-activated resins are used for underwater applications [99]. Overall, commonly used fibers are carbon, glass, aramid, and basalt with typical forms of reinforcement fibers as continuous (roving and woven) and discontinuous (chopped strand) [18]. Several FRP bridges and their used materials are exampled in Fig. 16.

FRP bridges should have sufficient strength and they need to be produced in a large size [17]. There are several manufacturing methods for FRP bridges' components consisting of pultrusion, Vacuum Assisted Resin Transfer Moulding (VARTM), and hand lay-up [102]. There are also new research studies on Filament Winding manufacturing in Canada and the US but there is not any field application yet [15]. Every FRP component needs a special method of manufacturing, depending on the material properties, production rate, size, and cost.

The hand-layup method is appropriate for manufacturing large components while it is more labor intensive, inconsistent in the quality of produced parts, and low fiber volume fraction compared with automated methods. Besides, environmental and health concern of styrene emission is an issue about hand-layup manufacturing. VRTM is suitable for manufacturing small- to medium-sized and complex parts at intermediate volumes rate, allowing limited production to run cost-effectively. However, VRTM needs expensive tools and equipment. In addition, it is more complex than the hand-layup method and lower dimensional tolerances than the pultrusion method are available. There is also the possibility of compromising the mechanical properties of the finished FRP structure because of resin's low viscosity using VRTM. On the other hand, the pultrusion method creates consistent quality and it is the only known method that ensures sufficiently, keeps evaporation of solvents at a minimum. 3D printing as a new understudying method is a rapid and easy manufacturing method. Furthermore, it is ideal for complex components (but limited wide size) while it is usable in a dangerous environment. However expensive equipment and materials are needed and only limited material can be used [21,49,103].

Face sheets of sandwiched structure decks are usually composed of a resin (such as vinyl or polyester) and fibers such as glass [48,65]. The most common material used for the core is thin-walled honeycomb FRPs or rigid polymer foam [65] by VARTM or hand lay-up technology [62]. Adhesively bonded FRP pultruded shapes are manufactured in the required geometric shapes from glass and carbon FRPs using the pultrusion process for pultruded decks, girder, or beams [13]. Pre-preg and wet lay-up manufacturing processes are used for repairing the substructures of bridges with different materials such as glass, carbon, or a hybrid of these fibers [37]. Two different wrapping methods were used for repairing the substructures of deteriorated water bridges. "Dry" wrap requiring cofferdam construction for preventing water contact during the FRP application and cure, and a "wet" wrap that could be applied and cured in water [99]. Fig. 17 shows the manual and automatic wrapping of the Gandy bridge's piers and Seomjin Bridge, respectively. There are also limited efforts to use 3D printing as a new approach to the construction industry, which results in a faster and cheaper manufacturing process. The world's first 3D printed steel/cement bicycle bridge (Netherlands) and footbridge (Amsterdam) were built in 2017 and 2019, respectively [104,105], but there is no full-scale whole 3D printed FRP bridge yet. The Royal HaskoningDHV built the first 3D printed bridge prototype (see Fig. 16) comprising of glass fibers and a thermoplastic resin [106]. 3D printed FRP bridge could transform the future of the bridge industry, not only by speeding up the construction but also making the process more cost efficient [103], alongside the possibility of producing complex shapes, increasing versatility and sustainability.

The present FRPs are sustainable [107] in terms of time and energy consumption in comparison with conventional steel/concrete materials. However, further studies are needed to develop a new generation of green FRP bridges using natural fibers (such as flax, hemp, jute, or wood) and thermoplastic resins. Thermoplastic resins and natural fibers need lower production energy for both manufacturing, recycling, and disposing of these materials [10,40,108]. So, these resins and natural fibers are expected to be used more widely in the bridge industry due to a lower negative impact on the environment.

Table 4
FRP applications for Department of Transportations in the US for repairing deteriorated substructure's components [101].

State name	Projects name
California	Caltrans I-5 & Hwy2, Los Angeles, Caltrans Hwy, Fashion Square, Broxton Parking Structure
Connecticut	Big Foot Overpass
Georgia	Georgia Pier Cap
Illinois	Rte. 116 over Folky Slough, Archer Ave. Rte. 171, Rte. 64 West of Rte. 59, Polar Street
Indiana	I-69 Overpass, U.S. 14 Bridge Column
Kansas	I-70 Topeka Ave., I-5 Overpass column
Missouri	Lindberg Ave. Traffic Light
Nevada	Sparks
New Hampshire	Pembrook
New Jersey	Timber Creek Overpass
New York	Railroad Bridge City of New York
Ohio	Akron Sewer Rehabilitation
Pennsylvania	Pennsylvania Lakawanna County, I-276 over Old York Rd.
South Carolina	I-85 Bus Overpass, Cainhoy Road
Tennessee	I-40 Harpeath River
Texas	I-635 Dallas & Marsh Lane, I-37 & New Braunfels, I-10 & San Jacinto River, US Highway 69, I-635 Marsh, I-37, Beaumont 69
Vermont	Vermont DOT
Virginia	Off Route 250 N.E. between Gayton & 621, Rte. 29 Bridge over Rapidan River
Washington	Mannette Bridge
Wisconsin	Wisconsin (I-90 at Church St. Madison), Wisconsin (I-94 at Rte 12/18 Madison), Wisconsin DOT (I-90OVER Route 14 E at Janesville)

6. Future challenges

There exists a growing interest in the future of FRP bridges. However, as shown in Fig. 18, major challenges also exist (see Fig. 18). These challenges are highlighted in a survey questionnaire and follow-up interviews in 2019 with 44 United States Departments of Transportation and 2 Canadian agencies [94].

Other studies also reported that lack of standard design codes for FRP, basic understanding of benefits, right price and reliability are key challenges for the management of FRPs [6,7]. The majority of the transportation agencies referenced design and practice guidelines published by AASHTO and ACI 440, however, considerable manufacturers use their own experience [94]. As a result, FRP bridges have not yet reached their maximum capabilities and require additional research [7]. In addition, high factors of safety have been applied to the schemes carried out so far, which have reduced the efficiency of designs because of the lack of experience, and long term reliability data under fatigue and environmental loads [109]. The challenges facing the FRP bridge industry is not dissimilar to that faced by previous industries—such as steel and concrete—upon the introduction of new materials to a well-established marketplace. When iron was first used as a building material, it was created into shapes that looked like timber. Conceivably the FRP bridge parts of tomorrow will progress to take more advantage of the material properties and manufacturing methods of FRP materials. Therefore, there is still a need for future research and development activities to improve the experience and comfort with the FRP bridges by addressing the following technical needs.

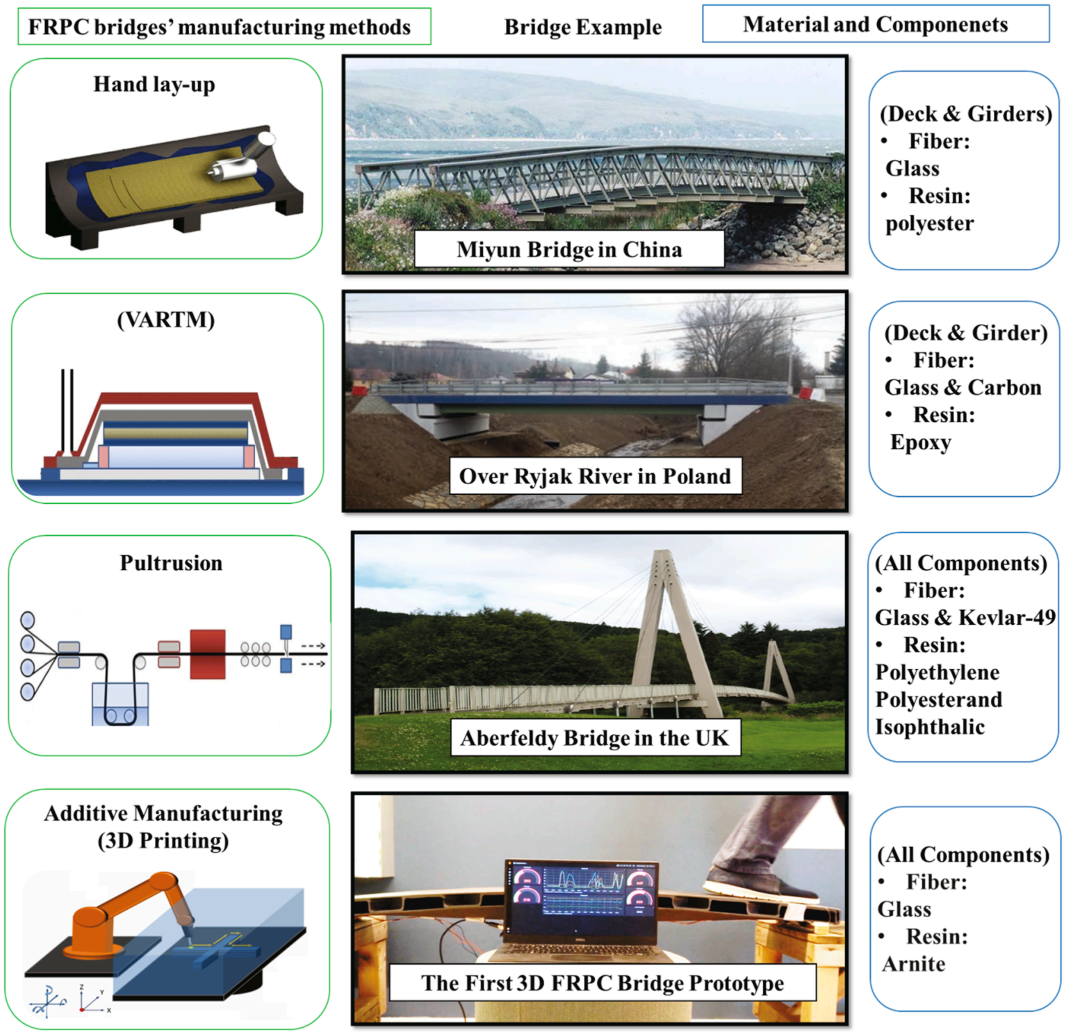

Fig. 16. Manufacturing methods and commonly used materials in FRP bridges. A double column fitting image.

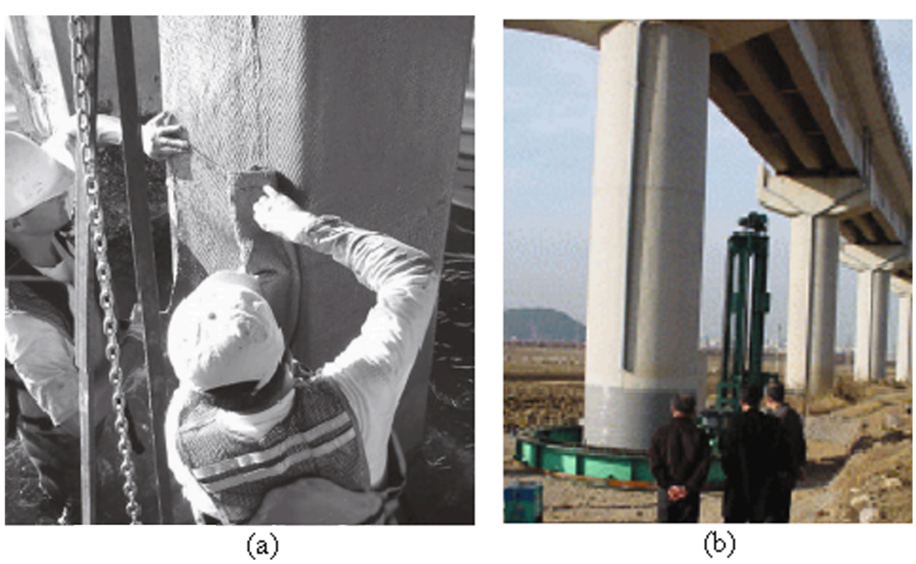

Fig. 17. Repaired piers using a) manually (Gandy bridge) [36] b) automatically wrapping (Seomjin bridge) [24]. A single column fitting image.

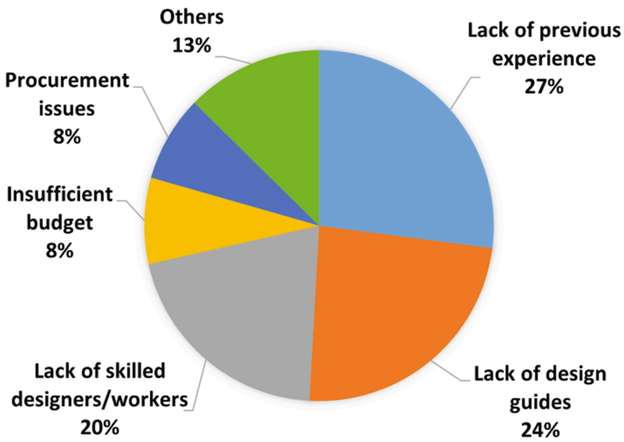

Fig. 18. Challenges in using FRP for bridge projects [94].

- Development of design standards and guidelines
- Fatigue and environmental loads durability characteristics
- Efficient design and characterization
- Cost effective materials and manufacturing solutions
- Recyclability and end of life characteristics

7. Conclusion

The paper provides a comprehensive review on the application of FRPs in bridges. Fast erection, light weight, high corrosion resistance and better fatigue and seismic behavior are reported as significant features which make FRPs attractive as a sustainable solution in the bridge industry. The FRP bridges are efficient in both structural performance and durability. Beside the advantages, there are uncertainties in relation to FRP bridges including life cycle cost evaluation and lack of a complete guideline for manufacturing. In addition, more works need to be done to develop cost effective, flexible, and automated manufacturing solutions, and development of green composites, made of natural fibers and recyclable plastics, to provide more sustainable FRP bridges.

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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