AUSTROADS BRIDGE CONFERENCE 2025
Brisbane | 25-27 June 2025

Peer reviewed paper

On the use of Glass Fibre Reinforced Polymer Reinforcement in Civil Structures

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Abstract

Steel reinforced concrete makes up a significant proportion of the material used in construction of civil structures. Its widespread and long-standing use has led to its performance being well understood by designers, constructors and asset owners.

Whilst over time there have been significant improvements to concrete mix designs, detailing practices and construction methods, the susceptibility of steel reinforced concrete to deterioration from reinforcement corrosion remains an ongoing risk to its long-term performance. With an increased focus on construction of sustainable infrastructure, consideration of use of alternative construction materials is becoming increasingly prevalent.

Glass Fibre Reinforced Polymer (GFRP) is a viable alternative to steel reinforcement for many applications in civil structures, offering several significant benefits compared to steel reinforcement, including:

- Improved durability
- Lower embodied carbon
- Light-weight

This paper discusses the benefits listed above, the background and history of its use, key design considerations, recent examples of use in civil structures, and potential future applications.

Keywords: GFRP, Sustainability

1. Background and history of use

International

The invention of fibre-reinforced polymer (FRP) is attributed to Leo Baekeland, who presented his invention in 1909 at a meeting of the American Chemical Society, giving it the name Baekelite (New York Time 1909)[1]. Recognising the benefits of a strong, stiff and mouldable material, the 1930s saw much research into potential applications into the aviation industry. The method of mass-producing fibres was discovered by accident, when a researcher directed a stream of compressed air into molten glass (the method was later patented).

The rapid expansion of transport infrastructure in the US post World War 2 prompted state road authorities to investigate alternatives to steel reinforcement, primarily as a means to combat accelerated deterioration of bridges that had been observed in aggressive environments (often exacerbated by the use of de-icing salts). Several alternative materials and protective coating systems were considered including hot-dip galvanising, powder resin coating, alloyed steel, epoxy coating, and GFRP. Epoxy coating was widely adopted as the preferred system for aggressive environments, with inadequate supply scale of GFRP the reason for it being non-preferred.

In the 1980s, medical facilities housing MRI equipment required the buildings to be constructed with non-conductive reinforcing material, creating a demand for GFRP reinforcement. The subsequent upscaling of supply combined with concerns about the observed poor performance of epoxy coated reinforcement, led to GFRP reinforcement being reconsidered for use in civil infrastructure.

Since the 1990s, use of GFRP reinforcement in bridge construction in Canada and the US has become widespread. Notable publications of design standards include:

- 2006 Canadian Highway Bridge Design Code CAN/CSA-S06-06
- American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings 2012
- American Concrete Institute (ACI) Guide for the Design and Construction of Structural Concrete Reinforced with Fibre-Reinforced Polymer (FRP) Bars ACI 440.1R-15 (ACI 440)

With many civil structures having now been in-service for over 25 years, the performance of GFRP reinforced structures has been the subject of much assessment and evaluation. These studies have consistently shown bridges are performing well, with little to no sign of deterioration.

A prominent example of adoption of GFRP reinforcement in civil structures is by the Florida Department of Transport (FDOT). Many of the civil structures in Florida are located in aggressive environments such as marine locations and inland water crossings with acidic water.

Figure 1 Example of bridge deck reinforcement corrosion leading to concrete spalling

FDOT have accepted the significant benefits offered by GFRP reinforcement, with permitted use now including:

- Approach Slabs.
- Bridge Decks and Bridge Deck overlays.
- Cast-in-Place Flat Slab Superstructures.
- Pile Bent Caps not in direct contact with water.
- Pier Columns and Caps not in direct contact with water.
- Retaining Walls, Noise Walls, Perimeter Walls.

- Road Barriers.
- Pedestrian/Bicycle Railings.
- Reinforced Soil Structure (RSS) Panels.
- Drainage Structures.

Figure 2 Example of bridge deck reinforced with GFRP

Source: https://www.coastlinecomposites.com/market/frp-concrete-reinforcement/frp-reinforce-bridge-decks-caps-footings/

Note: the authors acknowledge GFRP reinforcement has been widely used in structures in Asia and Europe, most notably China, Japan and Germany. This discussion has highlighted US and Canadian work as, historically, much of the design requirements in Australian Standards originates from these countries.

Australia

In civil structures in Australia, GFRP reinforcement has historically been limited to use in tunnelling, where it is used in discreet sections at the start and ends of driven and bored tunnels. Known informally as a 'soft-eye' these sections are reinforced GFRP in lieu of steel, allowing tunnelling equipment (TBMs and road-header) to easily penetrate the structure by locally crushing concrete and rupturing the reinforcement. This construction technique minimises damage to the equipment and surrounding structure. Typically, the sections of structure directly adjacent to the 'soft-eye' are reinforced with steel.

In 2022, the Pound Road West Project was constructed in Victoria. The project was delivered by Major Roads Projects Victoria (MRPV) on behalf of the Victorian State Government, constructed by Seymour Whyte Construction Pty Ltd (SWC) with SMEC Australia Pty Ltd (SMEC) as the lead designer. The project involved construction of a new arterial link between existing roads, requiring construction of a new bridge over rail and long lengths of retaining wall on the bridge approaches. The ultimate asset owner/maintainer was the Department of Transport and Planning (DTP).

During the project design phase, the steel reinforcement supply chain was being heavily disrupted due to the Covid-19 pandemic. This led to SWC investigating alternative materials, and GFRP was quickly identified as a viable alternative to steel. It was readily available in Australia, cost effective and offered several other benefits discussed in subsequent sections of this paper.

SMEC proposed using GFRP reinforcement in the concrete panels of a post and panel retaining wall. The application was nominated for the following reasons:

- Only straight bar was required, no custom bar shapes.
- The element tension face was exposed, and any deterioration or distress would be visible.
- The wall was offset from the main road carriageway, and not close to third-party assets. Major repair works could be carried out (if the wall was observed to be performing poorly) with minimum disruption.

Due to the absence of any local precedence or Australian Standards for concrete structures with GFRP reinforcement, the project delivery team worked with DTP to demonstrate the proposed application was acceptable. Much of this work involved research into similar applications internationally.

Figure 3 Pound Road West - Post and panel retaining wall – panels reinforced with GFRP

The Pound Road West retaining wall construction was completed in June 2023, and has performed as expected to-date.

Following the successful use of GFRP reinforcement on the Pound Road West Project, an opportunity for larger scale use became apparent on the Calder Park Drive Level Crossing Removal Project. The project, which is currently in construction phase, involves construction of a new road bridge over rail and long lengths of RSS retaining wall on the bridge approaches.

This project is being delivered by the Metropolitan Roads Projects Alliance (MRPA) on behalf of the Victorian State Government. SMEC are engaged by Fulton Hogan (the MRPA constructor) for the project detailed design, and Rockfield Technologies Australia Pty Ltd (Rockfield) for RSS design.

Figure 4 Calder Park Drive RSS – RSS facing panels reinforced with GFRP

Over 260 RSS concrete facing panels of size (approximately) 2 m x 2 m have been constructed and installed on the Calder Park Drive Level Crossing Removal Project. Since the project commencement, GFRP reinforced RSS facing panels has been adopted on the following additional projects:

- Ferris Road Level Crossing Removal Project
- Maidstone Street Level Crossing Removal Project.

2. Benefits and shortcomings

This section summarises the advantages and challenges of GFRP reinforcement when compared to conventional steel reinforcement. While GFRP offers a range of significant benefits, particularly in sustainability and performance in harsh environments, it also presents several limitations.

Benefits of GFRP reinforcement

Several studies highlight the numerous benefits of GFRP over conventional steel reinforcement, which can significantly influence its adoption in various construction applications.

Durability

GFRP is highly resistant to corrosion, a critical factor in the durability of reinforced concrete structures. Unlike steel, which is susceptible to rust in harsh environmental conditions, GFRP performs better in severe exposure areas, offering extended service life with minimal maintenance requirements.

Lower embodied carbon

Life Cycle Assessment (LCA) studies demonstrate that GFRP reinforcement results in up to 40-80% reductions in carbon emissions compared to steel over the life cycle of a structure. Studies have shown that GFRP emits 17% less CO_2 equivalent per kilogram throughout its life cycle, and when comparing the total emissions of GFRP to steel, reductions ranging from 78% to 85% are observed across different construction configurations. These results highlight GFRP as a more sustainable alternative to traditional steel in terms of carbon footprint (Al Omar & Abdelhadi, 2024)[3]. A recent project completed in Melbourne for a Reinforced Soil Structure had an estimated reduction of over 50% based on kg CO_2 per cubic metre of concrete.

Light-weight properties

GFRP rebars have a density of approximately 2100 kg/m^3, which is significantly lower than that of steel. This lower weight facilitates easier handling during construction, reduces transportation costs and contributes to the reduction of CO_2 emissions during logistics and assembly.

Electromagnetic neutrality

While not typically required in Civil Projects, the electromagnetic neutrality of GFRP means that it does not conduct electricity or magnetic fields. This makes it ideal for applications where electromagnetic interference is a concern, such as in hospitals or MRI rooms.

Shortcomings of GFRP reinforcement

While GFRP offers substantial benefits, it also presents several challenges that must be considered for its practical use in construction.

Limited bar shapes

Unlike steel, which can be easily bent on-site, GFRP bars can only be shaped during the manufacturing process. As a result, all bends, ligatures and hooks must be finalised before ordering. This limitation restricts flexibility during the placement of reinforcement in the field.

Lack of ductility

Although GFRP has a higher tensile strength compared to steel, it is not ductile. As a result, GFRP does not undergo a gradual deformation before failure, and its failure mechanism typically involves concrete crushing.

Lower modulus of elasticity

The Modulus of Elasticity for GFRP is significantly lower than that of steel, typically around 60 GPa, which is about 30% of the modulus of steel reinforcement. This reduced stiffness can affect the serviceability of concrete structures, particularly in applications where deflection control is crucial. It can also lead to wider crack widths compared to an equivalent steel-reinforced section.

Safety concerns during cutting and handling

When cutting or handling exposed GFRP, workers must use personal protective equipment (PPE) to prevent injury from the fibres present in the material.

Fire performance

The stiffness of GFRP tends to decrease at lower temperatures compared to steel. This reduced performance in high-temperature environments may limit its application in certain fire-sensitive structures. However, for many Civil Structures, exposure to fire is less likely.

Shear capacity

Due to its lower stiffness, GFRP reinforcement results in a reduced shear contribution from the concrete elements (i.e. Vuc) compared to steel-reinforced sections of similar depth. This limitation is attributed to larger crack widths, which reduce aggregate interlock and compromise the overall shear resistance of the concrete.

3. Design considerations

The basic methodology used for steel-reinforced concrete can be applied to GFRP with code-specific adjustments and additional checks to represent long-term and environmental behaviour.

Local design standards

There is currently only one Australian Standard relating to GFRP – AS5204:2023[4]. This standard is for the manufacture of the reinforcement itself, rather than the design of the reinforced section. The use of GFRP for strengthening of existing bridges has been utilised far more than the use of GFRP reinforcement in new structures, as evidenced by AS5100.8[5] Appendix A providing guidance on FRP strengthening of existing bridges, where the Concrete Design part, AS5100.5[6], only relates to steel reinforcement.

State transport authorities have made limited mention of GFRP in their specifications, as shown in Table 1.

Table 1 Summary of state specifications relating to GFRP

State	Authority	Specification	Comments
Queensland	Department of Transport and Main Roads	MRTS271	References CSA S806 as an example of international design code. No design specific requirements.
Victoria	Department of Transport and Planning	Nil	-

State	Authority	Specification	Comments
New South Wales	Transport for New South Wales	Nil	TfNSW have published a Technical Guide for "Design of Continuously Reinforced Concrete Pavement using Glass Fibre Reinforced Polymer (GFRP) Bars at Traffic Loop Location"
South Australia	Department of Infrastructure and Transport	Nil	-
Western Australia	Main Roads Western Australia	Nil	-
Northern Territory	Department of Logistics and Infrastructure	Nil	-
Tasmania	Department of State Growth	Nil	-

The authors understand that some state transport authorities are in the process of drafting specifications and/or technical guidelines on the use of GFRP reinforcement. Until that happens, designers must utilise international design standards for the GFRP reinforcement in new structures.

International design standards

The most common standards relating to GFRP are listed in Table 2.

Table 2 Summary of international design codes relating to GFRP

Country	Standard Title
United States of America	ACI Code 440.11-22 - Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary
Canada	CAN/CSA-S807-10 (R2015) - Specification for Fibre-Reinforced Polymers
	CAN/CSA-S806-12 (R2017) - Design and Construction of Building Components with Fibre-Reinforced Polymers
	CAN/CSA-S6-14 (2014) - Canadian Highway Bridge Design Code" Section 16: Fibre Reinforced Structures
International	ASTM D7957-22 (2022) - Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement

ACI440.11 design considerations

The authors utilised ACI Code 440.11[7] for the examples given within this paper. Notable points regarding the ACI440.11 design process are summarised below:

Flexural strength

Flexural strength is determined based on the GFRP reinforcement ratio to the balanced reinforcement ratio. This dictates whether the section is governed by GFRP rupture, concrete crushing or a balanced failure (simultaneous concrete crushing and GFRP rupture).

Shear strength

Shear strength of the section depends on the concrete shear capacity and the capacity of the shear reinforcement. In members without shear reinforcement, such as many elements in civil projects, the shear capacity relies entirely on the concrete. Compared to a steel-reinforced concrete section with equal areas of longitudinal reinforcement, the GFRP reinforced section has a smaller depth to neutral axis after cracking, due to the lower axial stiffness. As a result, the shear resistance provided by both aggregate interlock and the uncracked flexural compression zone is smaller. No allowance is made for the dowel action of longitudinal reinforcement.

Deflections

For most civil structures, deflection of the concrete element is typically not the governing criterion. However, GFRP reinforced sections have a larger deflection compared to a steel reinforced section of equivalent reinforcement area. Therefore ACI440.11 does not permit control of deflection by satisfying minimum thickness requirements. Instead estimated deflections must be computed and compared to limiting values. ACI440.11 provides formulae for the effective moment of inertia based on the service and cracking moments.

Crack control

ACI440.11 provides maximum bar spacing limits to ensure crack widths to less than 0.71 mm. Though this is typically larger than the limits provided for steel-reinforced sections, it is an acceptable practice given the improved durability performance of GFRP. In the author's experience, some Road Authorities are hesitant to allow a larger crack width limit for GFRP and often require that the same predicted crack widths be used for GFRP and steel-reinforced sections (e.g. 0.2 mm maximum crack width). This requires additional GFRP reinforcement to achieve the crack width limits and can become the limiting design criteria. The bar stress and spacing formula rely on a Bond-Dependent Coefficient. Based on testing, this value can vary between 0.7 – 1.6 (ACI440.11)[7]. ACI440.11 provides a value of 1.2 so that 70% of crack widths would be less than 0.7 mm for all GFRP surface types. Some suppliers have test data for this coefficient, however many do not have.

Creep rupture

GFRP reinforcing subjected to a constant tension over time can suddenly fail after a time period called the endurance time. This failure mechanism is called creep rupture. GFRP reinforced sections should check the service load stress levels to ensure creep-rupture failure does not occur under sustained stresses. The creep rupture endurance time can irreversibly decrease due to adverse conditions such as high temperature, UV radiation exposure, high alkalinity, wet and dry cycles, freezing-and-thawing cycles, and abrasion of the reinforcement. To address this, the sustained stress in the GFRP reinforcement is limited to 30% of the design tensile strength. Many civil structural elements have a relatively high ratio of sustained load to design load, so this can become a governing factor in some instances.

Fire performance

GFRP reinforced concrete at high temperatures rely primarily on the GFRP reinforcement-concrete bond strength being maintained. ACI440.11 states that GFRP bars shall not be permitted where fire-resistance ratings are required. The commentary of ACI440.11 provides further information on detailing requirements to achieve non-bond-critical GFRP reinforcement to avoid anchorage failure in the event of a fire. Civil structures rarely require fire-resistance ratings, and are less likely to be exposed to fires, however it should always be considered on a project-specific basis.

4. Future applications in Australia

A review of applications of GFRP reinforced concrete civil structures internationally gives a clear indication of its potential use in Australia. The authors consider the absence of an Australian Standard for design is the most significant impediment preventing more widespread use. Its use relies on adopting recognised international standards (i.e. ACI440.11), the approval of which is at the discretion of the relevant asset owner/maintainer authority. The processes involved in being granted this approval are often onerous and time-consuming, and success relies on project delivery teams remaining committed to achieving their desired outcome. The authors have observed the confidence in GFRP in Australia has led conservative design parameters being a condition of its use (i.e. crack width and concrete cover). It is expected these conditions will be relaxed over time as confidence increases, leading to the full benefits of GFRP reinforcement being realised.

It is apparent that use of GFRP reinforcement in RSS facing panels is becoming preferred (in Victoria). In the absence an Australian Standard, expanding the list of applications in Australia is expected to be gradual. The authors recommend the following applications be considered by project delivery teams and state road authorities:

1) Sub-surface drainage pits
2) Precast culvert crown units
3) Bridge approach slabs
4) Culvert base slabs

These applications are (generally) at low risk of fire damage, difficult to inspect and repair (warranting enhanced durability), and do not warrant a high-level of ductility.

5. Conclusion

GFRP reinforcement as an alternative to steel reinforcement has been used in civil structures internationally for over 25 years. Use in Australia is relatively new, however it is apparent it is becoming preferred for some specific applications. The benefits making it an appealing alternative to steel reinforcement include its reduced mass, lower embodied carbon and enhanced durability. It is expected the use of GFRP reinforcement in civil structures will increase over time as confidence in its performance improves.

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