



# Bolted Joints in Fibre Reinforced Polymer Bridges



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## Abstract

Use of fibre reinforced polymer is becoming increasingly popular in FRP bridges. FRP offers high strength-to-weight ratio, corrosion and chemical resistance, and fast deployability. A major issue in its wider applicability is lack of understanding of joints. This paper presents a review of mechanical connection methods for FRP bridges. Slip and fatigue resistance are critical to any bridge design. While conventional methods of fitted bolts, rivets and high strength friction bolts are not suitable for FRP joints due to viscoelastic nature of the material, injection bolts offer cheap, convenient and reliable method of joining for FRP bridges. Injection bolts have been used in the past to repair old steel bridges. Inspiration is taken from these old steel bridges to see its potential in FRP bridges. The behaviour of resin injected bolted joints is tested in three stages: quality control tests, static creep tests and fatigue tests. Research shows that FRP joints with resin injected bolts have a promise in terms of achieving slip and fatigue resistance. Joints with injection bolts can withstand as much as 60% of the failure load applied in 4 million cycles. This proves that resin injected bolted joints can achieve comparable slip and fatigue resistance as high strength friction bolted joints. However, majority of research data is limited to testing single or double lap shear joints. More experimental and numerical research is needed to extend the characterisation of these joints to all FRP bridge components.

**Keywords:** FRP bridges; Bolted joints; Sustainable materials; Slip and fatigue resistance

## Introduction

Construction represents 10% of global economy and contributes to about one third of global carbon emissions. Green construction with digital design is the new way to make structures and infrastructure sustainable. One key driver is to use materials with lower environmental impact. Fibre reinforced polymer is one

of the sustainable materials with low carbon footprint, lightweight, and resistance to chemicals and corrosion. These are desirable properties for bridge engineering. Although, traditional materials, such as steel and concrete have been used in bridges for 150 years, FRP being relatively new material offers excellent opportunities for bridge engineering.



Figure 1: Dawlish footbridge, Exeter, United Kingdom [2].

FRP material offers high strength to weight ratio as compared to steel and reinforced concrete, which is attractive for bridge designers. This material has been used in various bridges including Dawlish bridge (Figure 1) Bonds Mill Lift Bridge and the 2014 Frampton Cotterell Bridge in England; Miyun Bridge in China; and Medway Bridge in USA [1] However, lack of awareness among bridge engineers and gaps in design standards including limited understanding of joints are two major hurdles inhibiting its wider use in bridge engineering. Pultrusion is the cheapest manufacturing method to produce standard FRP profiles as compared to hand layup, filament winding and resin transfer or infusion moulding [3]. These structural profiles can be joined through bolting, bonding or hybrid system where bolting and bonding are combined. Due to lower stiffness, design of FRP structures is generally governed by serviceability rather strength. Design in conventional materials, such as steel and concrete, is controlled by strength.

Bridge joints must be slip resistant for their reliable performance under fatigue loading. Preloaded high strength friction bolting (HSFB), hot riveting and fitted bolting are conventional ways to achieve slip resistance in steel bridges. None of these methods are suitable for assembling slip critical joints in FRP bridges. Hot riveting is unsuitable and obsolete due to lack of skilled labour, and health and safety regulations in Western Europe and North America. Also, FRP cannot withstand high temperatures in excess of 1200-1500 °C needed for hot riveting. Fitted bolts are expensive and impractical because they are machined on their shanks and installed in reamed holes. HSFG bolts transfer force by friction due to clamping force from preloading. This frictional force is lost over time due to FRP viscoelastic creep relaxation [1,4].

Resin injected bolts provide an alternative economical and practical solution to achieving slip resistance in bridges. Injection bolts were first used in 1970 in The Netherlands to repair old riveted steel bridges, cranes, heavily loaded crane girders, masts and towers [5]. Experimental investigation of these bolts was carried out at the Delft University of Technology, which resulted in design guidelines in the ECCS Recommendation No 79 [6]. This research provided an alternative method to achieving slip and fatigue resistant joints either in existing or new heavily loaded steel structures. Fatigue tests at Delft proved that the fatigue resistance of joints with injection bolts was comparable to riveted joints and better than joints with fitted and non-preloaded bolts.

### Joints with Injected Bolts in Steel Bridges

Resin injected bolts have been used in repair and rehabilitation of existing riveted steel bridges. Gresnigt & Stark [5] were probably the first to discuss design rules and method of installation of injection bolts. They also gave examples of use of injection bolts in repair and strengthening of existing structures and application in new structures. It has been a standard practice in the Netherlands since 1970s to use injection bolts to repair old steel bridges. It is also a common Dutch practice to use preloaded injection bolts in new railways bridges. Shock, fatigue and internal corrosion resistance are three key benefits of using preloaded injection bolts. The preloaded injection bolts were also used in new storm surge barrier in the waterway between Rotterdam and the North Sea.

There were two main reasons for choice of preloaded injection bolts. First, it eliminated any chance of slip and internal corrosion in the joint. Second, the design resistance in the injection bolts was higher than conventional high strength friction bolts. Injection bolts may be used as non-preloaded or preloaded. In the non-preloaded bolts, load transfers through bearing and shear of the bolt. In preloaded bolts, load is not only transferred through bearing and shear, but also by friction between the connected plates. One of the key conclusion by Gresnigt & Stark [5] was that preloaded injection bolted joints had higher design resistance than conventional HSFG bolted joints and resulted in compact joints.

Fatigue behaviour of both bolted and resin-injected bolted joints, in old steel railway bridges in Portugal, was studied by de Jesus et al. [7]. The authors took material from two bridges, Fao and Trezoi using double and single lap shear joints respectively. SIKADUR 30 was used as an epoxy to fill the injection bolts. Bolts were preloaded to 80Nm. The main aim of this work was to determine the fatigue strength rather than the slip resistance. The double and single lap shear configurations used stress ratios (R) of 0.0 and 0.1. The results showed consistent fatigue strength reduction in resin injected bolts. This was quite surprising outcome as Eurocode 3 [8] did not distinguish between preloaded standard connections and resin injected connections.

### Joints with Injected Bolts in FRP Bridges

Research on use of injected bolts in fibre reinforced polymer bridges is extremely scarce, with only a couple of research papers being published over past two decades or so. Wingerde et al. [9] were undoubtedly the first to demonstrate the usefulness of injected bolts in FRP joints. They carried out a number of static and fatigue tests on joints using pultruded FRP profiles. Both standard and resin injected bolted joints were tested. The joint consisted of two pultruded sections connected by web plates. They used stress ratios, R of 0.1 and -1 (maximum over minimum stress). Fatigue life of resin injected bolted joint showed only modest enhancement compared the joint with standard bolts for R=0.1. But for stress ratio of R=-1, reversed cyclic loading, the fatigue life was 100 times higher than the one with standard bolts. This suggested that resin injected bolted joints can be alternative to standard bolted joints in FRP bridges.

Zafari et al. [1] and Qureshi & Mottram [4] were the first to carry out overall fatigue performance testing of resin injected joints in FRP bridges. The testing consisted of quality control tests (often ignored in past research), static creep tests and fatigue tests. Quality control tests were performed to check filling and curing of resin. Static creep tests were used to determine design bearing resistance of resin. The bearing resistance determined in this way was used to establish the bearing stress ranges for fatigue testing. Finally, slip and fatigue performance was determined by testing the joints up to two and four million cycles.

### Quality control tests

The purpose of these tests was to check smooth filling in injection bolts. Eurocode 1090-2 [10] describes the method for machining injection bolts as shown in Figure 2. A small hole is drilled in bolt

hole to inject the resin. The resin then flows through clearance via an air escape in the bottom washer. The Connection becomes slip resistant once resin cures. ECCS 79 [6] suggests using a top washer with chamfered inside diameter as shown in Figure 3a. Qureshi & Mottram [3] tried two different two part resins Sikadur-30 and RenGel SW404+HY2404. Using the top washer in Figure 3b did not fill the clearance properly with resin getting stuck in the grooves of

the bolt. Two novel top washers, Figure 3c & 3d, with 6 and 12 hemispherical undercuts were then machined and tried. The top washer with 12 undercuts passed the resin smoothly and quickly. This was one of the most innovative contribution of this research work. To check smooth filling of the passage a trial injection bolt assembly using a Perspex tube was filled, as shown in Figure 4. These quality control tests were successful by using top washer in Figure 3d.

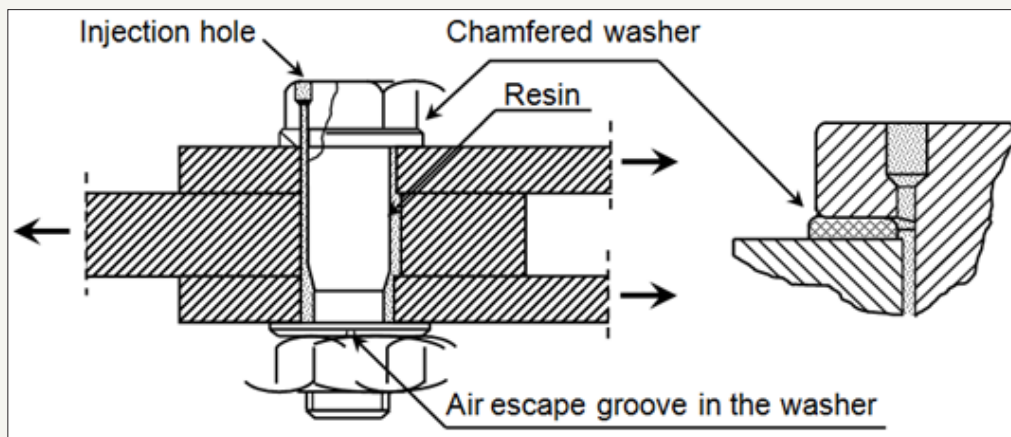


Figure 2: Machining injection bolt in a double lap joint [10].

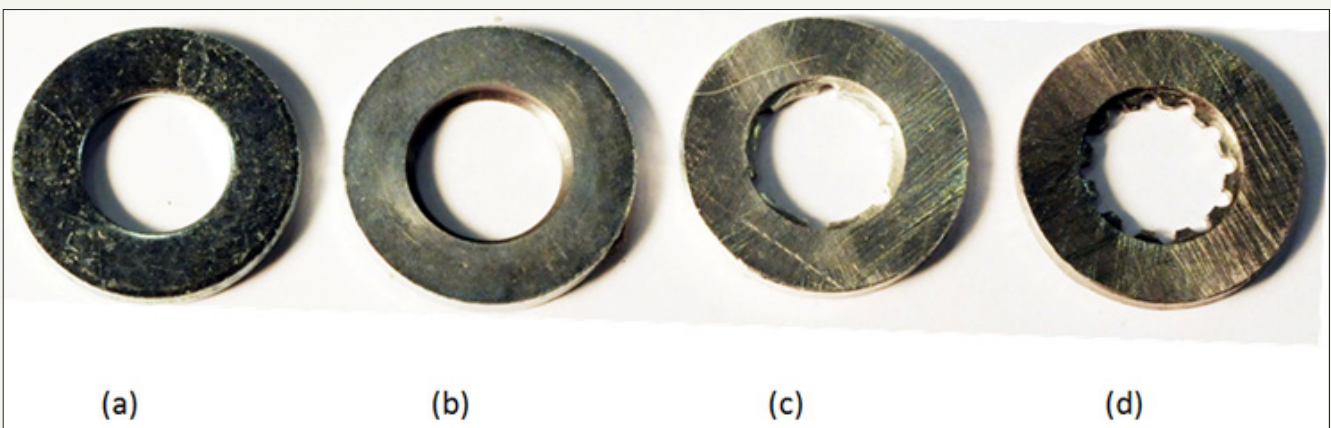


Figure 3: Details for the (top) washer under the bolt head [1].

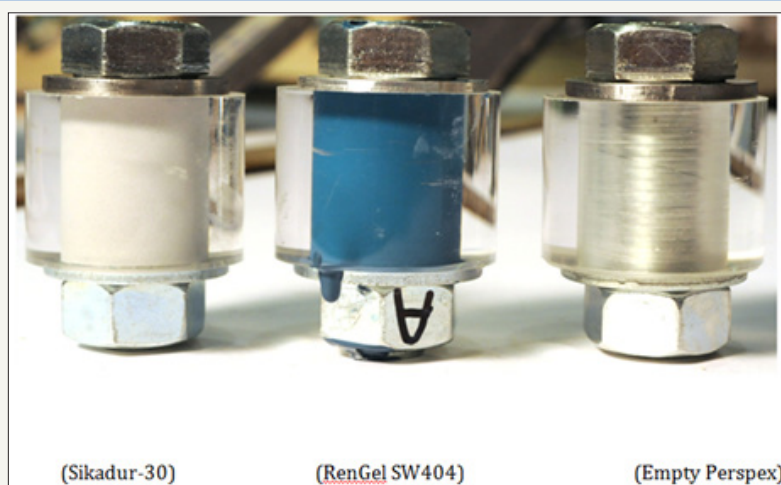


Figure 4: Empty and filled Injection bolts Perspex assembly [1].

**Table 1:** Test results on two types of M16 and M20 joints [5].

Type 1 (M16 with Thread in Bearing)			Type 2 M20 (with Thread in Bearing)		
Specimen Label	Mean Failure Load (kN)	Mean Bearing Stress at Failure Load (N/mm <sup>2</sup> )	Specimen Label	Mean Failure Load (kN)	Mean Bearing Stress at Failure load (N/mm <sup>2</sup> )
M16_18HL	72.3	240	M20_22.4HL	94.2	250
M16_16HL	80.1	266	M20_20HL	109.8	291
M16_RG	77.3	257	M20_RG	108.1	286
M16_SK	78.9	262	M20_SK	113.2	300

### Static creep tests

The main purpose of these tests was to determine the design bearing resistance of the resin. Figure 5 shows the test setup in [1]. Table 1 shows the mean bearing stress at failure for different tests. The number followed by M is bolt diameter, SK stands for Sikadur, RG for RenGel and 18HL means 18mm hole diameter. From Table 1, design bearing resistance for fatigue testing was chosen as 40% of the failure bearing stress, which comes out to be 32kN (106N/mm<sup>2</sup>) for M16 bolts and 40kN (130N/mm<sup>2</sup>) for M20 bolts.

### Fatigue tests

After determination of the design bearing stress of resin from creep tests, fatigue loading was applied to all joints with stress ratio, R=0.1. It means that for M16, the joints lower and upper tension limits were 3.2 and 32kN and for M20 joints 4 and 40kN. This is based on 40% of the mean tensile failure load. The specimens were subjected to 2 million fatigue cycles at a relatively low frequency of 2Hz. The main conclusion from this work was that even after 2 million cycles with loading equal to design bearing resistance, the joints exhibited only 0.2mm displacement. Some specimens were also subjected to 60% of the mean failure load and up to 4 million cycles. Even after a very high tensile loading and 4 million cycles, the specimens showed no signs of failure. This means that resin injected bolted joints can be successfully used in FRP bridges and can be classed as slip and fatigue resistant joints.

### Conclusion

A research review is presented on resin injected bolted joints. A very limited research exists on the behaviour of injected bolted joints, especially in FRP bridges. Resin injected bolts provide a robust, resilient and sustainable joining method in FRP bridges. The FRP joints with resin injected bolts can withstand as much as 4 million cycles of 60% of the failure load. Considering unsuitability of fitted bolts, rivets and HSFG bolts in FRP bridges due to

viscoelastic nature of the material, injected bolts provide an easy, practical and reliable mechanical connection method. However, more experimental and numerical research is needed to test full scale FRP bridge components.

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