CORROSION RESISTANT REINFORCEMENT FOR SUSTAINABLE BRIDGES AND UNDERGROUND STRUCTURES

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Abstract

Bridge decks and underground service structures are often exposed to extreme environmental conditions where structural damage due to corrosion is a common phenomenon. This results in reduced service life and expensive repairs. Fibre Reinforced Polymer (FRP) products such as reinforcing rods offer a potential viable alternative to the steel reinforcement, which would allow better service life for structures and much reduced concrete cover as theses bars require minimal environmental protection. Higher service life and reduced quantities of concrete used in FRP reinforced concrete structures can be an attractive feature in terms of sustainability.

Carbon FRP (CFRP), Basalt FRP (BFRP) and Glass FRP (GFRP) are the popular corrosion resistant bars that can be used to replace steel to produce more sustainable structures. A case study of two research investigations is discussed in this paper where GFRP and BFRP were used to replace the steel reinforcement without compromising strength and service behaviour of the structures. A comparison between the behaviour of steel reinforced structures with similar FRP reinforced structures and the advantages of building sustainable infrastructure using corrosion resistant reinforcement is also discussed in this paper.

Key words: *Corrosion, FRP, steel, sustainability, concrete structures*

1.0 Introduction and background

1.1 Corrosion in deck slabs

Concrete can be a very durable material. However, the corrosion of steel reinforcement can cause severe deterioration to reinforced concrete structures which can result in spalling and cracking of concrete (Figure 1). Extreme environmental conditions cause chloride intrusion and carbonation in concrete structures that subsequently lead to expansive corrosion of steel. Expansive corrosion in steel reinforcement significantly reduces the design life and durability of concrete structures. There have been many incidents in the last two decades where bridge decks have either collapsed or undergone extensive repair due to steel corrosion. In some cases repair and maintenance costs, as a direct result of deterioration caused by steel corrosion exceeded the original cost of the structure (Read 1989).

Steel has been a prominent choice of structural reinforcing material in the construction industry since the early twentieth century. However, extensive corrosion due to de-icing salts and extreme environmental conditions have raised concerns about the service life of steel reinforced concrete structures. Several durable construction techniques have been introduced to the structures that are frequently exposed to vulnerable corrosive environments. High quality concrete, thicker concrete cover, steel protection methods such as epoxy coating and water proofing the structures have been popular methods adopted in an attempt to achieve durability. However, failures of such methodologies have raised concerns about their long term reliability.

Therefore, non-corrosive reinforcement such as fibre reinforced polymer (FRP) reinforcement and stainless steel bars have the potential to replace carbon steel reinforcement in bridge decks, if the serviceability, strength and safety are to be met. There are four types of FRP bars currently available in the market, namely Glass Fibre Reinforced Polymer (GFRP), Carbon Fibre Reinforced Polymer (CFRP), Aramid Fibre Reinforced Polymer (AFRP) and Basalt Fibre Reinforced Polymer (BFRP). Among the four types of FRP bars, GFRP and BFRP economically cheaper than AFRP and CFRP bars. Stainless steel reinforcement costs double that of GFRP. Therefore, considering economic factors and availability, GFRP and BFRP have been a popular choice in the construction industry.

Figure 1: Chloride induced corrosion damage (Courtesy: http://cce.oregonstate.edu)

1.2 Application of corrosion resistant composites in bridge decks

In-plane restrained slabs are inherent in much of bridge deck construction. To date, the benefits of arching action have not been fully realised to produce highly durable FRP reinforced concretes slabs in the world. The research discussed in this paper investigated the manner in which the benefits of arching action can be incorporated to effectively use GFRP reinforcement to replace conventional steel without compromising the strength, serviceability and safety of reinforced concrete slabs. Previous research studies have outlined preliminary findings [(Taylor and Mullin 2006), (Tharmarajah et al. 2008) & (Tharmarajah et al. 2009)] and this paper gives an overview of recent research at Queen’s University Belfast to investigate the behaviour of FRP reinforced slabs.

Although FRP reinforcement is appreciated for its better durability (Clarke 1993), there is a concern over the service and ultimate behaviour of FRP reinforced concrete elements. Much of the research on FRP reinforcement has been carried out on simply supported slabs where the lower modulus of elasticity can lead to higher deflection and bigger cracks on structures and failure could be catastrophic due to FRP rupture. However, the behaviour of in-plane restrained slabs are different from that of simply supported slabs, where the benefits of compressive membrane action enhance the service and ultimate behaviour.

1.3 Application corrosion resistant composites in underground structures

Underground concrete utility vaults/service chambers (Figure 2) are often used in communications, electricity and gas utility distribution networks to house vital connections. Prior to the 1960s, these underground structures were primarily constructed using bricks, cast-in-place concrete and/or concrete blocks (Munkelt, 2010). This type of construction was often slow and time consuming which resulted in costly infrastructure. Nonetheless, masonry construction is still adopted by some authorities around the world as their preferred construction method for underground service chambers. However, more generally, the rising popularity of precast concrete by the 1960’s identified it as a prime choice for underground structures due to its lower cost and speedier installation. Precast concrete elements were considered durable compared to cast-in-place structures and thus they became widely accepted in the industry. However, durability concerns for the steel reinforcement demand additional concrete cover (B.S. EN 1992-1-1 2006), which raises concerns over the sustainability and, particularly, the economic viability of this form of product.

As underground service chambers may be exposed to sulphate and chloride intrusion, they require adequate protection to prevent the reinforcement from corrosion damage. Therefore most design guidelines recommend larger minimum cover for structures exposed to such corrosive environments, relative to more inert exposure (Broomfield 2009). As these structures are generally subjected to relatively low bending moments in service due to a combination of very small spans and relatively low loading, this demand for extra cover can significantly increase the mass of the structures, while concerns over reinforcement durability may remain. Moreover, there is a considerable labour cost in the production of these units as relatively complex reinforcement arrangements are required to be tied by hand during the manufacturing process. If the underground service chambers could be produced either without reinforcement or with corrosion resistant reinforcement, then it may possible to reduce the cost of material and/or labour involved in the production process, yielding a more economically competitive product, with improved confidence in its durability, which would give competitive advantage to the precast manufacturer.

Figure 2: Typical precast underground service chamber box

2.0 Experimental Investigation

Two separate research studies are discussed in this paper. Two experimental investigation methods were adopted. For the slabs tested as representative full scale models of bridge decks, an in-plane retrained setup (Figures 3 & 4) was implemented and a simply supported test setup was used for the test panels of underground service chambers (Figures 5).

For in-plane restrained slabs, the test models were loaded with a knife edge line load at the mid span representing local wheel loading on a bridge deck slab using an accurately calibrated hydraulic actuator. A steel rig was used to represent the restraint of the supporting Y beams and the surrounding slab (Figure 4).

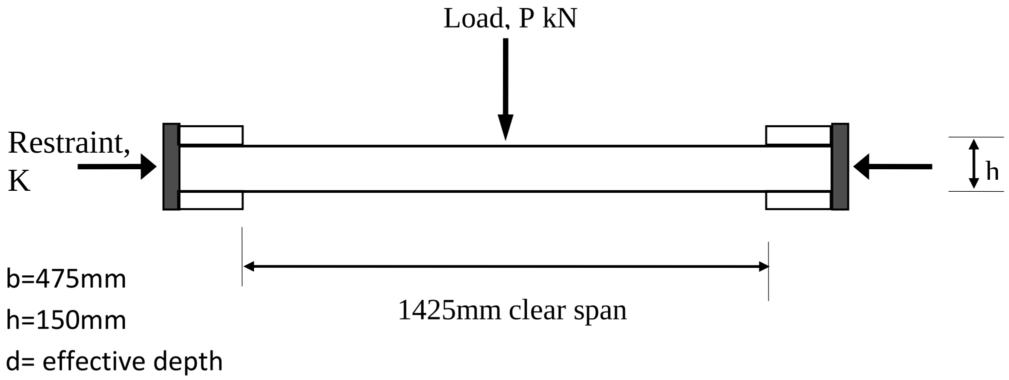

Figure 3 – Model Test Slab Set-up for restrained slabs

Figure 4 – Test rig and test arrangement for restrained slab

Test slabs of 1425mm length, 475mm width and 150mm reinforced with BFRP and GFRP bars were tested to study the behaviour of bridge deck slabs. The test parameters were reinforcement spacing and size.

Typical 100mm steel reinforced representative panels of underground service chambers were tested along with similar BFRP reinforced and unreinforced panels as a control sample. The panels were all 350mm wide and 1090mm long, allowing for a clear test span of 900mm. The panels were designed by the authors and constructed by a precast concrete manufacturer. Each panel was subjected to four-point bending, as described in Figure 5.

Given concerns, by some researchers and practitioners over the service behaviour of GFRP reinforced concrete slabs, the deflection and crack width and pattern were fully investigated within the service load range. Deflection was observed directly below the loading line using displacement transducers. The horizontal displacement at the end of the rig for in-plane restrained slabs was monitored using two 25mm transducers placed to monitor any lateral expansion due to arching thrust. Concrete cracking and crack width expansion were monitored with load increment.

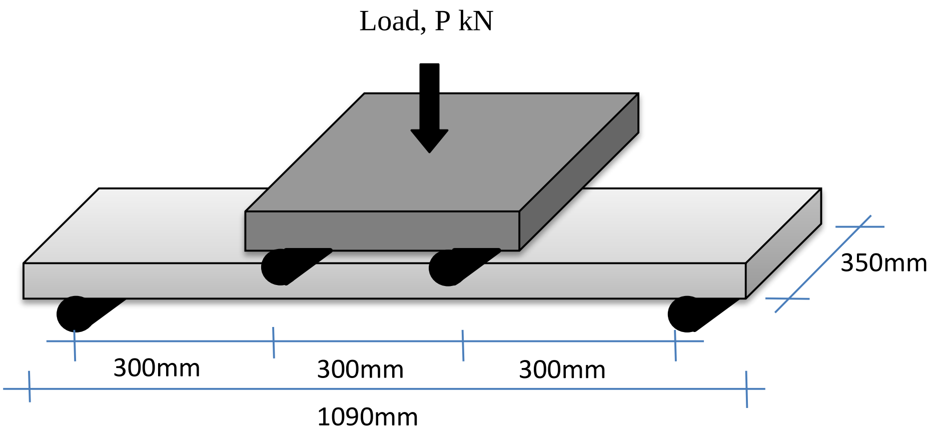

Figure 5 – Model Test Slab Set-up for simply supported slab

3.0Experimental Analysis

Four full scale representative models were used to investigate the service and ultimate behaviour of FRP reinforced in plane restrained slabs. First two slabs were reinforced with 0.6% GFRP reinforcement and the other two with 0.6% BFRP reinforcement. Among these sets, one was reinforced with 125mm spacing and the other was reinforced with 300mm spacing. The test results are provided in Table 1.

Another four simply supported panels were tested for underground service chambers. Two BFRP reinforced test panels, one steel reinforced and unreinforced panel were tested to compare the performance of the BFRP reinforced panel against the reference panel, reinforced with steel.

The service behaviour characteristics namely, deflection levels, measured crack width and failure modes are compared with the recommended guidelines.

Table 1: Comparison of test results with design guidelines recommendations for restrained slabs

Test slabs*	Balanced amount of rebar %	Actual rebar %	Deflection of the test slab at 150 kN$^+$	Ultimate failure load kN	Failure mode
GFRP 0.6%_12_125 T&B	1.13	0.60	l/408	343.5	Concrete crushing
GFRP 0.6%_16_300 T&B	1.10	0.60	l/445	364.9	Concrete crushing
BFRP 0.6%_12_125 T&B	0.60	0.60	l/383	300.4	Concrete crushing
BFRP 0.6%_16_300 T&B	0.55	0.60	l/361	295.1	Concrete crushing

*Labelling convention: GFRP 0.6%_12_125 T&B: Bar type & percentage_bar size_effective depth of reinforcement_position of reinforcement

$^+$ Maximum single axle load

Table 2: Test results of simply supported slabs

Test panel*	Balanced amount of rebar %	Actual amount of rebar %	Deflection at service load of 17kN	Ultimate failure load (kN)	Failure mode
Steel_60	3.19	0.67	L/526	56.3	Yielding of steel
BFRP_60	0.52	0.67	L/211	45.9	Concrete crushing
Unreinforced	N/A	N/A	N/A	13.8	Flexural
BFRP_70	0.52	0.67	L/271	52.5	Concrete crushing

*Labelling convention: Steel_60: Bar type_effective depth of reinforcement

The results in Table 1 shows that all the test slabs satisfied minimum service limits recommended by the design guidelines. ACI 440.1R-06 (ACI 2006), Eurocode (BS EN 1992-2 2005) and Canadian Highway Bridge Design Code (CAN/CSA-S6 2006) recommend the deflection should not exceed span/250 at the maximum wheel load level while the crack width should be less than 0.5mm for FRP reinforced structures as there are no corrosion issues associated with FRP bars. The 0.5mm width limit was defined based on aesthetic appeal of the structure.

Table 2 compares the deflection ratio, defined as the supported span divided by the deflection at the service load, ultimate failure load and failure mode. Currently, there is no deflection limit for the target underground service chamber products, which is agreed between the client and the precast manufacturer. For initial analysis of these composite reinforced sections, a benchmark deflection limit of L/250 at service load level for combined earth, water and surcharge pressure is employed.

Conventional analysis techniques employed by the precast manufacturer based on existing design data have yielded a critical ultimate design load of 25.3kN for one of their most common service chamber sizes and was adopted as the target bending moment resistance of the panels. Table 2 shows that both steel and BFRP reinforced panels demonstrated a load capacity well above of the ultimate design while BFRP bars reinforced at 60mm effective depth (BFRP_60) marginally fail to satisfy the acceptable deflection criteria at service load level.

Figure 6: Condition of GFRP inside a tested slab (No indication of rupture on bars)

Figure 7: Ruptured GFRP during material test

Independent of the reinforcement arrangement and type, all the FRP reinforced test slabs have failed by concrete crushing. The failure of simply supported FRP reinforced slabs was due to reinforcement amount higher than the balanced amount of reinforcement and failure of in-plane restrained slabs was due to in-plane restraint and arching action. Failure due to concrete crushing is considered a marginally better mode of failure than FRP rupture as FRP rupture could lead to catastrophic collapse. All of the slabs showed recovery in deflection after the peak loading and there was no evidence of complete GFRP rupture or BFRP rupture noticed when the embedded bars were examined after tests (Figure 6 and Figure 7).

These two research studies lead to industrial application where the civil infrastructure benefited from corrosion resistant FRP bars. The experimental investigation and research on FRP reinforced in-plane restrained slabs at Queen's University Belfast has lead to the application of BFRP bars in Thompson's bridge. Two thirds of the bridge deck was reinforced with BFRP bars except the cantilever section and tested for serviceability and strength.

The research outcome on underground service chambers enabled the precast manufacturer to replace steel with BFRP bars, thus reduced the amount of concrete used by up to 15%.

4.0 Industrial Applications

Thompson's bridge is a two way A-class road bridge located in county Fermanagh of Northern Ireland (Figure 8). A new bridge was proposed to be built at the site as the previous road bridge was found unsuitable to carry wide loaded vehicles that frequently use this stretch of road.

Figure 8: Thompson's bridge

The superstructure comprises 'W' precast pre-stressed beams with a reinforced concrete slab bridge deck, where two thirds of the 10.9m wide deck was reinforced with BFRP non-corrosive reinforcement (Figure 9). The slab was reinforced with 0.6% amount of reinforcement for both top and bottom layers.

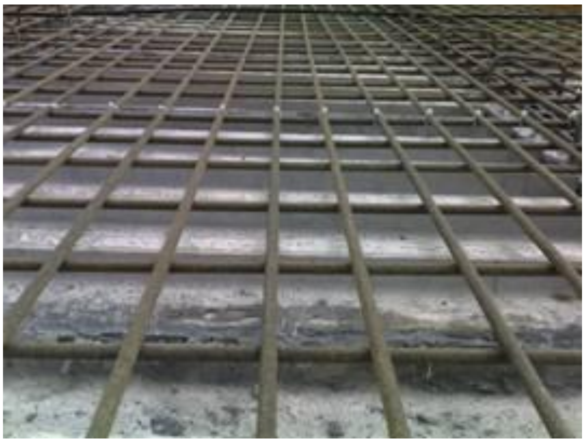

Figure 9: BFRP reinforced deck

The bridge deck was tested by applying a simulated wheel load up to 400 kN. The initial tests showed FRP reinforced deck performed on par with similar steel reinforced section for service behaviour. The promising test results expand the future opportunity to use non-corrosive FRP bars in restrained slabs.

5.0 Conclusions

The following conclusions were drawn from this experimental study.

- FRP reinforcement can replace conventional steel reinforcement in concrete structures.
- Restrained slabs can have substantial ultimate capacity even with less amount of reinforcement.
- FRP reinforced in-plane restrained slabs showed acceptable service behaviour in terms of deflections and crack widths.
- When reinforced with at least 0.6% amount reinforcement, FRP bars satisfy all the service limit criteria recommended by various design guidelines such as ACI 440.1R-06, CHBDC etc.
- FRP reinforcement can be replaced in underground service chapters without compromising the strength and service behavior as the strength of FRP reinforced panels far above the required strength.
- Replacing steel with FRP bars in underground service chambers can save considerable amount of concrete that used as cover concrete.

Therefore GFRP and BFRP reinforcement can be a substitute for steel in restrained slabs and underground service structures which are exposed to extreme environmental condition.

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