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MONITORING OF THOMPSON'S BRIDGE BFRP REINFORCED DECK WITH DISCRETE OPTICAL SENSORS

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ABSTRACT: Over the past 20 years many concrete bridges have exhibited problems associated with reinforcement corrosion and their repair can cause disruption to traffic and the associated costs of congestion are high. A further problem for bridge deck slabs is the need carry heavier lorries under increased European loadings. This paper describes the replacement of corrodible steel rebar with corrosion resistant basalt fibre reinforced polymer (BFRP) rebars in a bridge deck slab and monitoring of their performance in comparison to steel rebar using discrete optical sensors and other SHM techniques. Thompsons bridge in Northern Ireland, is beam and slab bridge and the deck was cast with self-consolidating concrete (SCC) to further improve the durability and lower the carbon footprint. The SHM regime assisted in the acceptance of these new materials and in mitigating the risk by demonstrating excellent structural performance. It was concluded that the BFRP reinforced concrete bridge deck slab exhibited similar behaviour to the equivalent steel reinforced bridge deck slab. The maximum test load was nearly three times the current maximum European wheel load. The strain values were very low and 8.5 times less than the rupture strain of the BFRP bars at an applied load of 40t which is far in excess of the current EU wheel load of 15t. The BFRP rebar provided an alternative corrosion resistant system which can substantially improved whole life performance compared to corrosive steel rebar.

1 BACKGROUND

This project addressed the vitally important area of durable bridge deck construction and offered the opportunity to investigate an alternative to corrosive steel reinforcement, namely basalt fibre reinforced polymer bars (BFRP). It provides a unique opportunity for the continued monitoring of a durable highway structure which will be of benefit to all asset managers of such structures. Thompson's bridge is a replacement bridge carrying the two-way, trunk road in Co. Fermanagh, Northern Ireland. The bridge is a fully integral single span skew bridge. The superstructure comprised 'W11' precast pre-stressed beams with a reinforced concrete slab bridge deck. Fibre reinforced concrete formers were used as permanent formwork between the W-beams. The mid-span section was constructed with Basalt Fibre Reinforced Polymer bars of 12mm diameter and the remaining slab had 12mm steel reinforcement. Figure 1 shows the

placement of FBG sensors on the BFRP. Table 1 presents the details of the deck slab and the percentages of BFRP, steel reinforcement and the compressive strength of SCC.

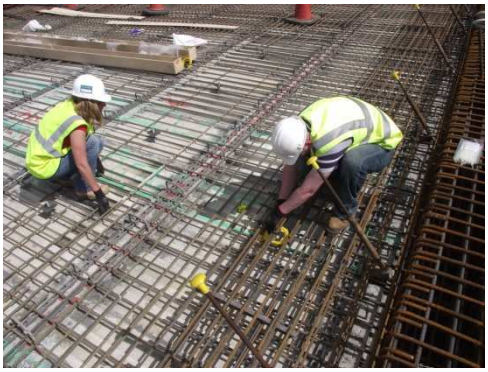

Table 1. Details of the deck slab

Effective span	1.4m between W-beams 1.6m over W-beam
Depth of deck	200mm
Phase 3	6.35
Depth of deck	200mm
Width of bridge	11.850m
Reinforcement	0.6% BFRP in central region 0.8% steel in outer
SCC compressive strength	50.5N/mm^2 (at time of tests)

Figure 1: Placement of optical sensors

2 TEST DETAILS

2.1 Test loading and instrumentation

The test areas are shown in Figure 2. One of the main criteria for SHM was to assess the influence of the reinforcement type on the service behaviour of the bridge deck slab. The central region of the bridge deck slab had 0.6% BFRP reinforcement and the remaining slab had 0.8% steel reinforcement. Test regions 1 to 4 incorporated BFRP reinforcement and Test regions 5 & 6 have steel reinforcement. Concrete cube samples were taken for each batch to ascertain the strength at the time of testing. A simulated wheel load was applied to each test panel using a self-straining test rig. A typical test arrangement is depicted in Figures2. A circular concentrated load was applied at the midspan of each test panel via a 300mm diameter steel plate bedded on soft board. The application of load was from an accurately calibrated 500kN hydraulic jack system and the test rig was assembled with the top beam horizontal about both axes thus minimizing eccentricity effects. A spherical seating was located between the ram and the loading beam to minimize the effect of any possible misalignment of load. Five electronic displacement transducers, with ±0.01mm accuracy and 25mm travel, were positioned along the centre line of the panel at midspan , quarter span and near support. This enabled a profile of the deflected shape from the midspan towards the beam supports for each load increment.

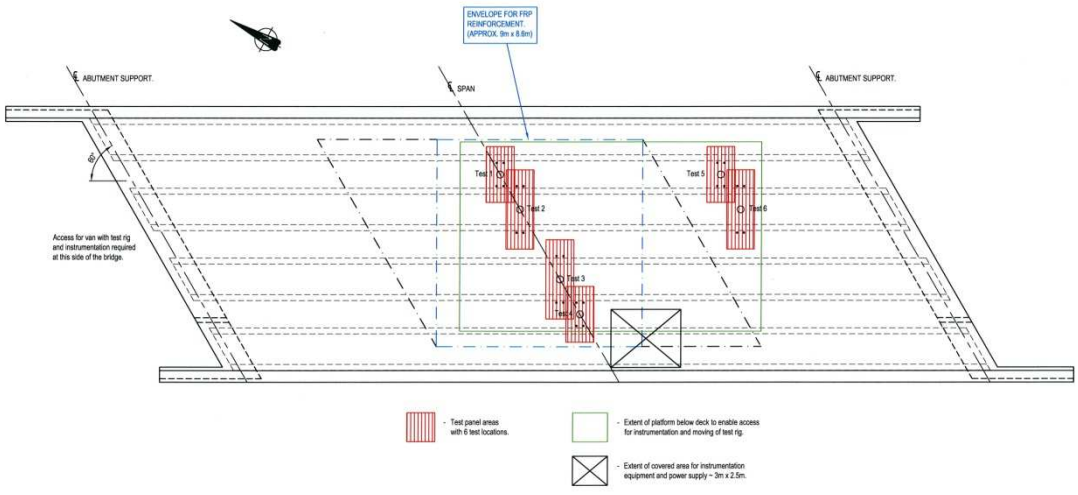

Figure 2: Test Panel arrangement

Fibre Bragg Gratings (FBGs) for strain measurement have been used successfully in bridge monitoring and have many advantages over more conventional sensors (Taylor et al, 2008). FBG's rely upon a change in strain causing a shift in the characteristic wavelength of light reflected back along (or through) the optical fibre where the grating is written. The equation used to determine the reflected wavelength, λB, is defined by the Bragg condition:

$$\lambda_B = 2n_e\Lambda \qquad \text{(Equation 1)}$$

where n_e is the effective refractive index and Λ the periodic spacing of the grating

Figures 3 show the workings of an FBG. In this bridge, five FBG sensors were written onto each optical cable and three cables attached to three rebars in each of the BFRP test areas and adjacent to the test load Rebars A & B were in the bottom layer and Rebar C was in the top layer.

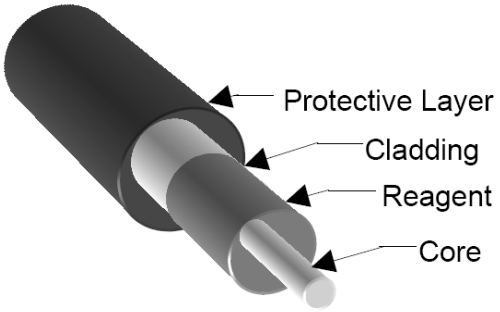

Fig. 3a. Schematic of workings of (FBG) (FBG)

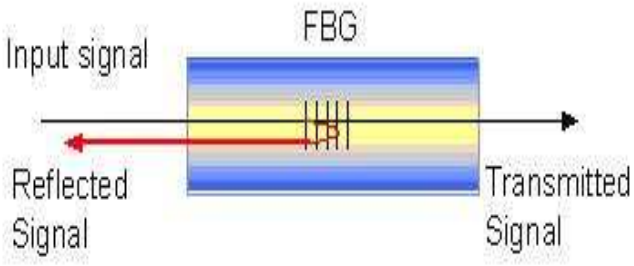

Fig.3b: Layout of a Fibre Bragg Grating

2.3 Test Procedure

Load was applied in 5kN increments at each of the test areas. Deflection and microstrain values were recorded at each load increment. Two test loads of 50kN were applied prior to the full test loads. The third or full test load (up to 400kN) was also applied incrementally. The intention was to apply a load of over twice the current maximum wheel load (that is, 150kN for the European Tandem System wheel load and incorporating a dynamic amplitude factor (DAF)) whilst not exceeding a midspan deflection of 2.0mm. However, this load was exceeded in all the test panels and a 400kN load was applied at the single concentrated load point with no detrimental effect to the deck slab. The soffit and surface of the concrete deck slab were observed at each increment of loading. It was not possible to see the soffit of the structural slab due to the permanent FRC formers but the crack pattern in the soffit of the formers was observed.

3 EXPERIMENTAL RESULTS

3.1 Deflection measurements

The deflections at either side of the loaded area are virtually the same, which indicated very little eccentricity in the test arrangement. Under the second service test load, the recovery in the deck slab for all of the tests was in excess of 90%. A comparison of the midspan deflections, transducer T3, under the full test load for each of the test panels is shown in Figure 4 for the 1.6m span slabs (that is, the maximum deflection in each test area). The deflections were similar in all of the test area and all below 2mm at a maximum load of 400kN or 40t. However, it can be seen that the test regions with steel reinforcement had slightly higher deflections and particularly test region 6 compared with test regions 2 and 3. This was probably due to slight variations in the depth of the deck or because of increased compressive membrane action due to variation in the concrete compressive strength. The magnitude of the deflections was low in all of the tests panels up to the maximum applied test load. In the 1.6m spanning slabs, the deflection at an applied load of 300kN (or twice the European wheel load) varied between 0.33mm (test area 2) and 1.14mm (test area 6) which was equivalent to a maximum of span/1404 in the slab with steel reinforcement. In the 1.4m spanning slabs, the deflection at an applied load of 300kN (or twice the European wheel load) varied between 0.3mm (test area 1) and 0.48mm (test area 5) which was equivalent to a maximum of span/2917 in the slab with steel reinforcement. This indicates extremely low deflections and well within current acceptable limits for reinforced concrete elements and is due to the beneficial influence of compressive membrane action on service behaviour. The areas of slab with BFRP reinforcement showed lower deflections than the equivalent steel reinforced areas of slab.

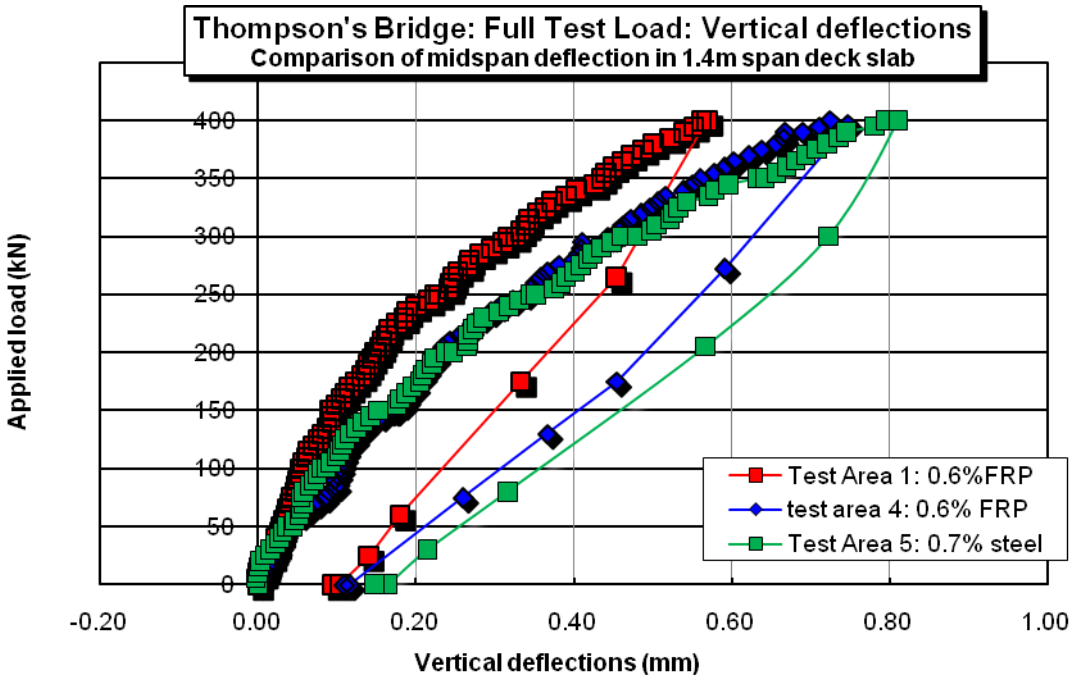

Figure 4: Comparison of midspan vertical deflections in test areas between W-Beams

3.2 Microstrain measurements

The results for the microstrain in a typical BFRP reinforced test deck slab areas are given in Figures 5 and 6. The strains at either side of the loaded area are virtually the same which indicated very little eccentricity in the loading. The maximum strains, as expected were in the bars in the bottom layer that were in tension (positive values_. The maximum value of strain recorded was 1993με in test region 4. Table 2 show the material properties of the BFRP bars based on the average of tests on control samples. The measured ultimate strain of the bars was 17037με so the maximum value of strain at an applied wheel load of 40t was 11.7% of the maximum possible strain in the bar and represents a factor of safety of 8.5. This aligns with the very low value of deflections measured in these test areas and suggests that the applied load of 40t was well within the service loading of the bridge deck slab. The sensors also showed good recovery in strain after unloading.

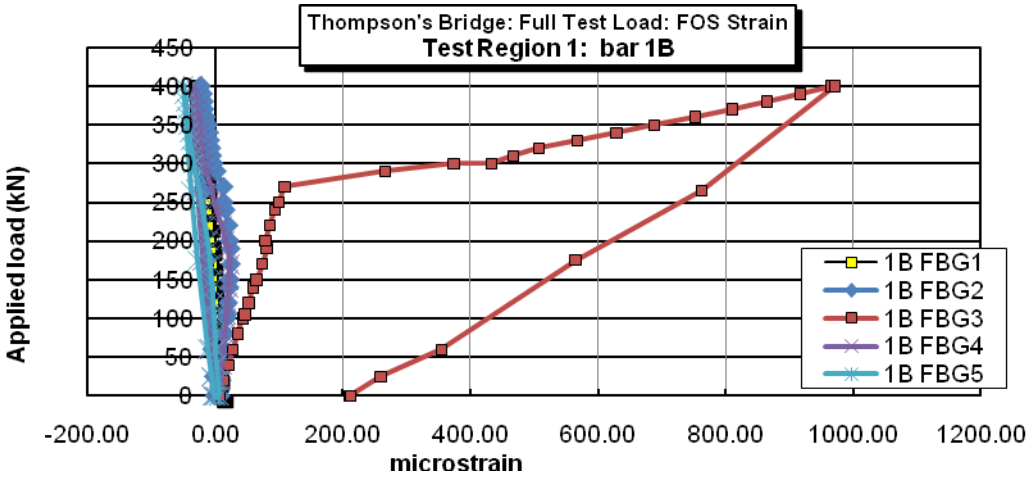

Figure 5: Micro strain in the underside of the bottom layer bar in Test Region 1

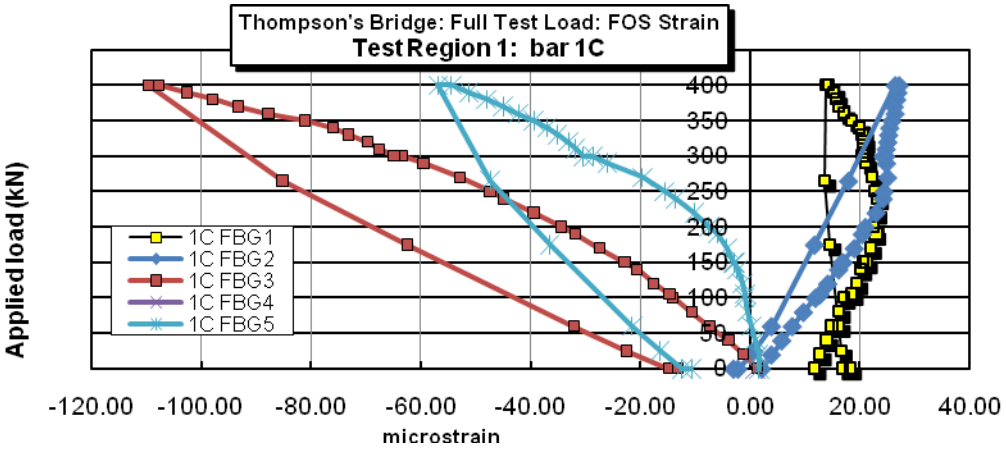

Figure 6: Micro strain in the top of the top layer bar in Test Region 1

Table 2: Reinforcement material properties

Reinforcement	**Tensile Strength (N/mm^2)**	**Elastic Modulus (kN/mm^2)**	**Ultimate Strain (με)**
BFRP	920	54	17037
Steel	539	210	2567

4 BACKGROUND TO COMPRESSIVE MEMBRANE ACTION

Slab and beam bridge decks are one of the most common forms of bridge construction in the Europe and the rest of the world (El-Gamal et al., 2007). Since these slabs are restrained against lateral expansion by the supporting beams, the application of vertical loading, such as a wheel load, result in compressive membrane action/arching action (CMA). This results in an enhancement in capacity above the predicted flexural capacity. If the benefits of CMA are used in conjunction with a durable reinforcing material then it is possible to provide bridge deck slabs with very low or zero maintenance, thus improving the whole life performance. BD81/02 outlines a means of assessing the true capacity of a deck slab by incorporation arching theory. Table 3 shows the predicted capacities using BD81 arching theory. It can be seen that, by taking into account arching action, substantially higher capacity is achieved than the capacities predicted using current flexural theory or elastic analysis. The strain results

Table 3: Predicted capacity using CMA theory from BD81

Concrete compressive strength* (N/mm^2)	**f'_c / γ_m**	**Rebar**	**d (mm)**	**Slab clear span (m)**	**h (mm)**	**L/h**	**k**	**ρe**	**P_{BD81} (kN)**
50.5	26.67	0.6% FRP	148	1.226	200	6.1	0.193	0.039	569

5 CONCLUSIONS

It can be concluded that the Structural Health Monitoring and the use of embedded discrete optical sensors enabled the construction of the first BFRP reinforced concrete bridge deck slab in Europe. The deck slab was capable of supporting a simulated concentrated wheel load of 40t with no detrimental effect. The FOS sensors showed that the strain values were well within the acceptable service limits. There was no visible cracking in the top of the slab and some hairline cracking in the permanent fibre

reinforced concrete formers at the soffit in the 1.4m span slabs. All of the test regions showed good recovery in deflection and strain after unloading.

The maximum test load was nearly three times the current maximum European wheel load. The maximum deflection in the BFRP slab was 0.78mm at an applied load of 40t and is equivalent to (effective span / 2054) which is well within acceptable limits for deflection. The maximum deflection occurred at the mid span and there was good recovery in deflection after the removal of all load. The strain values were very low and 8.5 times less than the rupture strain of the BFRP bars at an applied load of 40t.

ACKNOWLEDGEMENTS

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