ABSTRACT: Abercorn Bridge was built in 1932. It is located in Newtownstewart, Northern Ireland and is a ‘Hennebique Ferro’ integral reinforced concrete 4 span viaduct. The structure, being of the order of 84 years old, was showing signs of significant deterioration, so much so that one span was recommended for demolition due to its particularly poor condition. However, an alternative solution was proposed which offered to: retain all four spans; retain the overall aesthetics of the bridge; restore additional load capacity; preserve the bridge for at least a further 25 years; and reduce refurbishment costs. The alternative solution was adopted. Detailed inspection and testing of the bridge provided an accurate view of the bridge’s condition thus allowing a concrete repair scheme, incorporating cathodic protection, to be designed. A finite element analysis (FEA) model was created to allow the bridge to be more rigorously analysed, particularly comparing its as-built, deteriorated state and refurbished conditions. Importantly, the FEA model indicated that the repair scheme on its own was not sufficient to restore the required load capacity and an innovative, lightweight, structural over-slab was incorporated. This “bespoke” over-slab was among the first such projects to use a combination of basalt reinforcement and lightweight aggregate concrete to create a strong yet lightweight slab. To increase the confidence of the alternative, innovative solution, Fibre Bragg Grating (FBG) sensors were used to: monitor the bridge during repairs; ensure the structural behaviour was consistent with the FEA model; and confirm that the over-slab was working integrally with the bridge deck beneath. A final load test was undertaken on completion of the Works to ensure that the required load capacity had been achieved. This paper describes in more detail the remediation process.

KEY WORDS: Abercorn Bridge; Bridge Remediation; Concrete Repair; Cathodic Protection; Finite Element Analysis (FEA); Basalt Reinforcement; and Lightweight Aggregate Concrete.

1 INTRODUCTION

Abercorn Bridge (Figure 1) was built in 1932 and is located in Newtownstewart, Northern Ireland. The bridge, being of the order of 84 years old, was showing signs of significant deterioration and had a weight restriction of 3 tonne Gross Vehicle Weight (GVW). Due to the extent of the deterioration, the scope of works within the tender for repair included for the demolition and reconstruction of span 4 as well as concrete repairs to the remaining 3 spans. An alternative proposal was submitted by McFarland Associates Ltd, in conjunction with Graham Structural Solutions, using novel technologies and materials, in which span 4 was retained while still meeting all the required targets with regards to strength and life span. This paper gives an overview of the restoration project with a focus on the innovative approaches which have differentiated it from most other bridge remediation projects.

2 DESCRIPTION OF STRUCTURE

The structure is a ‘Hennebique Ferro’ integral reinforced concrete 4 span viaduct. The Hennebique system was among the first methods used to construct reinforced concrete structures in the UK [1]. The bridge spans the river Strule with a 30° skew. Spans 1 to 3 are positioned over the river and are supported on reinforced concrete piers which are in turn supported on a series of piles. Span 4 is located over the south west river bank and is supported by reinforced concrete piers and three lines of reinforced concrete columns supporting the three transverse deck beams. Spans 3 and 4 are effectively independent of each other with a buried expansion joint running the full width of the bridge structure and through the adjoining piers.

The bridge is constructed from seven key elements:
- A 178mm thick reinforced concrete deck slab;
- Longitudinal reinforced concrete beams;
- Transverse reinforced concrete beams;
- Reinforced concrete parapet edge beams;
- Large reinforced concrete piers;
- Reinforced concrete columns; and
- Integral reinforced concrete abutments.
An inspection of the bridge, undertaken in November 2006, identified shear cracking of the span 4 southern edge beam. This prompted a structural check to be carried out on the bridge structure, the findings of which indicated insufficient shear capacity with the cracked edge beam element. As a result a single lane restriction and 3 tonne GVW limit was imposed upon the structure.

3 INSPECTION AND TESTING

Various phases of inspection and testing works had been carried out over the years and the following extracts from inspection reports [2] indicate the condition of the key elements of the bridge:

3.1 Deck Slab

The majority of the deck slab soffit was in poor condition. This was evident in the extensive amount of spalling that revealed heavily corroded reinforcement. The main sources for this deterioration was the extensive areas of low concrete cover to reinforcement coupled with the ingress of chloride (de-icing) laden water from the road above. Electrode potentials were generally highly negative suggesting corrosion cells were initiated, particularly in the southern third of the 3-span bridge.

3.2 Pier Beams

The condition of the pier beams varied across the structure. One of the pier beams was in a very poor condition, largely due to a defective movement joint over. This pier beam had a crack running through it center measuring 15 mm at soffit level which penetrated the full depth of the beam. Other pier beams in the structure were in a more reasonable condition with only localised defects, most notably at the southern ends, where corrosion cells appeared to have been initiated.

3.3 Transverse Beams

Concrete had spalled on a number of the transverse beams and overall, their condition ranged from reasonable to poor. Corrosion cells appeared to have initiated in some of the beams but these were contained to localised areas.

3.4 Secondary Longitudinal Beams

The condition of the secondary longitudinal beams varied throughout the structure from reasonable to poor. A number of corrosion cells appeared to be active, the majority of which were concentrated on beams at the southern half of the structure.

3.5 Half-Cell Potential Survey

To give a more complete view of the condition of the bridge, prior to any repair works being undertaken, a half-cell potential survey was undertaken on any elements not previously tested. The half-cell technique measures the potential of steel reinforcing bars in the concrete in comparison with the known electrode potential of a reference electrode (half-cell). This potential of steel in concrete is an indicator of corrosion activity. When presented in the form of equi-potential contour plots, the half-cell potential survey proved a great tool for indicating where active corrosion was taking place and was thus the basis for the cathodic protection design.

4 FINITE ELEMENT ANALYSIS

For the purpose of aiding design and for validation of design concepts, a finite element analysis (FEA) model of Abercorn Bridge was produced.

The analysis software “LUSAS” version 14.7 was used to create the FEA model. The bridge model was created using “Thick Beam” and “Thick Shell” elements for the concrete beams and slab respectively. Figure 2 shows a section of the FEA model.

The FEA was undertaken using the original “as built” drawings for geometry and steel reinforcing arrays. Geometry was then confirmed during a series of site visits. Material properties were determined from various concrete cores and steel samples obtained from the bridge and tested in UKAS accredited laboratories. Areas of greatest interest were given a finer mesh, allowing for more comprehensive results to be obtained in these areas whilst minimising the amount of computation time required to analyse the FEA model. Analysis of the FEA model was undertaken using the single axle and single wheel load cases outlined within tables 5.3.1 and 5.3.2 of BD21/01 [3].

Initially, the FEA was used to check the capacity of the bridge in its deteriorated state. From this assessment, it was determined that span 4, even if fully repaired, would be unable to take the increased load specified, namely 10 tonne GVW. The FEA was then used to verify various design concepts for strengthening of the bridge.

To ensure that the FEA was accurately modelling the behaviour of the bridge, a “calibration” load test was carried out. For this load test, the bridge was subjected to a known load which was also modelled through FEA. The actual stresses measured could then be compared with the theoretical computations. Figure 3 shows the stress distribution in the concrete slab as a result of the load imparted on to the bridge.

The validated FEA model was then used for the design of various elements throughout the project, notably, the effects
of a substantial access scaffold being “hung” from the bridge. It was also possible to model various scenarios at any stage of the project timeline to determine the impact not only to the bridge as a whole but to individual structural elements also. For example, during the resurfacing of the bridge, the strains caused by the required plant were determined and confirmed to be within acceptable limits before the work could commence.

The FEA allowed efficient and confident decisions to be made throughout all stages of the project and was a vital tool in the success of the refurbishment.

5 DESIGN

The follow section outlines the significant design aspects of the Abercorn Bridge project.

5.1 Structural slab

To allow span 4 to be repaired, rather than demolished, a strengthening scheme was required to facilitate the extra loading required on the bridge. Using a combination of the FEA and traditional structural assessment methods, it was determined that a traditional over slab method would increase the self-weight to a point where the over-slab would be more of a detriment than a benefit. To counteract this, the structural slab was designed, in accordance with Eurocodes, to increase the load carrying capacity while minimising the increase in dead load of the bridge.

With this in mind, two lightweight materials were chosen for the structural slab: lightweight aggregate concrete; and basalt fibre reinforced polymer (BFRP).

Lightweight aggregate concrete has a number of advantages over traditional concrete, the most important being the reduced self-weight. The placed density of traditional concrete can vary from 2800 to 3100 kg/m$^3$ and has an average dry density of 2400 kg/m$^3$. Lightweight aggregate concrete, however, has a typical placed density of 2200 to 2400 kg/m$^3$ and a dry density of 1800 kg/m$^3$. Therefore, the use of lightweight concrete represents a reduction in self-weight of 33% placed and 25% cured compared to traditional concrete. Other benefits include a higher cement content than traditional concrete and a lower water cement ratio making it less permeable. The higher water absorption of the aggregate also ensures a better hydration of the cement. With this in mind, it is worth noting that the aggregate must be pre-soaked prior to mixing. Lightweight aggregate concrete also has a 33% reduction in thermal expansion coefficient, compared with traditional concrete, thus reducing the potential for cracks.

Basalt fibre is a high performance non-metallic fibre made from basalt rock melted at high temperature. The manufacture of basalt fibre requires the melting of the quarried basalt rock at about 1,400 °C. The molten rock is then extruded through small nozzles to produce continuous filaments of basalt fibre. The basalt fibre is then woven into a mat or pultruded with epoxy resin into reinforcement bars. BFRP’s main properties that make it a suitable replacement for steel reinforcing are its: high strength; low weight; high resistance to corrosion; and high tensile modulus. BFRP has 2.2 times higher tensile strength than steel, of the same diameter. This in combination with the fact that Basalt is 3.7 times lighter than steel makes it ideal when trying to reduce the dead load in a design. [4] As stated previously, basalt has a high resistance to corrosion as it does not rust or absorb water. This allows for a significant reduction in concrete cover thus allowing for thinner, lighter sections and more flexibility in design.

Commercially, lightweight aggregate concrete costs versus traditional concrete are generally comparable. BFRP reinforcement has higher initial costs versus steel, however, savings will be realised early on in the project due to the reduction in haulage costs, reduction in craneage/hoist costs and increased efficiency on site. Further savings are also realised during the lifetime of the structure through reduced maintenance costs and the removal of the risk of corrosion or degradation through chloride ingress or other contaminants.

One additional measure in the construction of the over slab was the placement of T12 shear pins at 2m centres along the longitudinal beams. This ensured that the existing deck and over-slab performed integrally. Prior to the installation of the overslab and the shear pins, the deck was milled to create a roughened surface. This imparted a degree of cohesion between the existing deck and the new over-slab. However, the design intent accounted for the shear pins as the sole mechanism for longitudinal shear resistance.

Once installed, the lightweight structural slab provided greater load dispersion than the original asphalt on its own and enabled the load carrying capacity of the bridge to be increased from 3 tonne GVW to 18 tonne GVW, a value that was significantly above what was thought possible (10 tonne GVW). Furthermore, the lightweight slab also increased the effective depth to tension steel thus increasing the deck flexural resistance.

The design of the integral over slab was undertaken using both “traditional” calculations and FEA modelling. Figure 4 shows the placement of the BFRP mesh prior to the pouring of the lightweight aggregate concrete.

![Figure 4. placement of the BFRP mesh prior to the pouring of the lightweight aggregate concrete](image)

5.2 Repair works

Concrete repairs were undertaken to all cracked, delaminated and spalled concrete as identified through a visual and “sounding” survey. Hydrodemolition (ultra high pressure water) was the chosen means of removal of defective concrete. This method of concrete removal has several benefits over “traditional” removal of concrete using breakers.
as the process: maintains the structural integrity of the reinforcing steel; cleans the steel of surface corrosion, washes off any surface contaminants and cleans out pits; and avoids fracturing the parent concrete behind which forms the repair face. In addition, no dust is produced and in the case of this project, the water was captured after the operation to eliminate any risk of contamination of the river.

In the context of applying a cathodic protection (CP) system as part of the concrete repairs, the extent of concrete removal could be limited to the concrete that was identified as being defective. There was no need to extend the length of breakouts beyond that which was already delaminated or spalled save to provide a mechanical key behind the reinforcement. This meant that large areas of concrete, where reinforcement corrosion had been identified through the half-celling, could be retained. Another benefit of applying CP is the removal of the need to apply a steel primer, saving both time and money. Concrete reinstatement was through traditional means with hand placed concrete repair materials being used for small repairs and sprayed concrete repair materials for the larger areas, which was the case for the majority of repairs on this project.

After the repair of the concrete elements of the bridge and the installation of the CP system (Section 4.3) a “levelling” mortar was applied prior to the application of a uniform, anti-carbonation coating. Figures 5 and 6 show the concrete elements prior to and after repairs had been undertaken.

Other repair works included resin injection of concrete cracks and the replacement of a buried expansion joint between spans 3 and 4.

5.3 Cathodic Protection

Corrosion is an electrochemical process involving both anodes and cathodes. Metal is lost (corroded) at the anode and this in turn protects surrounding areas (cathodes). It is the expansion of the metal at the anode, through corrosion, that cracks, delaminates and ultimately spalls cover concrete. Various electrochemical treatments exist for the prevention of corrosion and these involve the passage of a current, either temporarily or permanently, thus making reinforcement completely cathodic. One such electrochemical process, using hybrid anodes, incorporates the early short term passage of an electrical current with a longer sacrificial phase of protection. Hybrid anodes have provided a cost effective remediation solution for a wide variety of structures around the world. [5]

The cathodic protection system for Abercorn Bridge was designed with simplicity of installation, uniform current delivery, cost and robustness in mind. There are various stages that are considered in the design process, first of which is determining the most appropriate generic anode system.

DuoGuard Hybrid Anodes were used for the cathodic protection of the bridge. This system consists of an anode, encapsulated in a mortar, buried in drilled holes in the reinforced concrete structure. The DuoGuard hybrid anode is a dual technology anode based on the use of a sacrificial metal in both an impressed current and sacrificial anode role.

The system is designed to deliver a short-term, high, impressed current treatment to rapidly arrest the steel corrosion process. This impressed current phase usually lasts about 7 days and minimises further corrosion induced damage [5]. After a week the system then delivers a low current sustained treatment to ensure durability with low maintenance requirements. The DuoGuard system also retains the facility to re-apply further charge at any point in the future.

For aesthetic reasons, a discrete embedded method of installation was carried out. The size of anodes is part determined by design considerations such as lifespan and reinforcement content and part by practicality of installation. Figure 7 shows the installation of a typical anode.
structure. In addition, four monitoring zones were installed on the transverse pier beam between Spans 3 and 4 in accordance with BS EN ISO 12696:2012 [6] using buried manganese dioxide reference electrodes. These zones were chosen following the detailed half-cell survey and corrosion rate readings to identify the locations most at risk of future corrosion activity and should therefore be representative of the installed system as a whole. The monitored zones were connected to dedicated monitoring equipment installed on the edge beam of the bridge. This monitoring equipment was designed to record potentials and currents of the system which could then be used to verify the operation of the anode system and predict its future life.

5.4 Temporary works

Scaffold was required to provide access to the entire deck soffit as well as the outside faces of both parapets. The works area was required to be encapsulated to ensure no contamination of the river beneath. The scaffold was used at all stages throughout the project and as such had to be designed for a range of purposes. As assessment, using the FEA model, was undertaken to determine the impact of the scaffold which was designed to hang from the parapet walls. It was established from the assessment that the parapets provided a core strength to the structure and did not require enhancement. Figure 8 shows the installed scaffold supported from the parapet walls.

6 LOAD TEST

Four load tests were undertaken at various stages of the project:

- Confirm the new load carrying capacity of the entire structure.

For each of the load tests, fibre optic strain sensors were used to monitor the elements of the bridge while the required load was applied. The sensors used during load tests were Fibre Bragg Grating (FBG) sensors.

FBG sensors are made by laterally exposing the core of a single-mode, fibre to a periodic pattern of intense ultraviolet light. The exposure produces a permanent change in the refraction index of the fibre's core, creating a fixed index modulation according to the exposure pattern. This fixed index modulation is called a grating. When this grating is stretched or compressed by the change in length of the sensor, the reflective properties of the grating are altered causing the wavelength of the reflected light to change. It is this measured change which allows calculation of the strain. At each periodic refraction change, a small amount of light is reflected but the majority propagates through the grating with negligible attenuation or signal variation allowing the light to travel very long distances.

The sensors can be multiplexed on a single fibre optic cable that can be extended for very long distances, whilst only requiring one monitoring unit. Armoured and protected cable, which provides protection from mechanical damage, can be used in demanding outdoor applications such as Abercorn Bridge. Moreover, the fibre optic cable can undertake large strains of up to 2% elongation meaning significant movements can be monitored at early critical stages. The optic fibre conveys optical signal and not an electric one, this is greatly advantageous as there’s no electromagnetic interference and the presence of water poses no risk. Figure 9 shows the installed FBG sensors prior to load test.

The final load test was used to verify the load carrying capacity of the repaired and strengthened bridge. The load test was undertaken using a 6 axle calibrated lorry with a fully laden GVW of 44,000 kg. The load was applied in increasing increments of weight with the lorry travelling across Abercorn Bridge at 10 mph from north to south and when the lorry was returning over the bridge (south to north) it stopped directly over the sensors for a short period of time. This subjected the bridge to both a static and dynamic load. Several passes of the bridge were undertaken for each of the load increments to ensure consistent results were achieved. 2no. load tests were carried out to monitor all of the desired elements of the bridge. After the first load test was concluded, the sensors were removed and placed on further elements of the bridge for the second test.
To monitor the bridge elements while the lorry was travelling at 10 mph, a dynamic fibre optic interrogator was used to collect the readings. This interrogator is capable of taking 100 readings a second from each of the installed sensors. Figure 10 shows one of the graphs produced during one of the passes of the 44 tonne lorry. The first section of the graph shows the initial pass of the lorry at 10 mph and the second shows the lorry in a stationary position over the sensors.

![Dynamic Load Static Load](image)

Figure 10. Strain During 44 Tonne Load Test.

After each increment of the load test, the maximum strain was determined from the results obtained. These maximum strains were then compared to the theoretical strains from the FEA model confirming as to whether the bridge was performing as expected at every stage of the load test. The results at every stage corresponded with the FEA model and so the maximum load of 44,000 kg was reached during the load test. This final load test confirmed that the required load carrying capacity was reached.

7 CONCLUSIONS

Through the use of novel technology and materials it was possible to prevent the partial demolition of the Client’s asset while increasing load carrying capacity and fully meeting the Client’s brief. These methods will hopefully be used in the future as a basis for sustainable asset management.

The finite element analysis was produced in the early stages of the project enabling design concepts to be efficiently checked with regards to their suitability. This meant that more time could be spent detailing the chosen design and this ultimately saved on the design costs.

Fibre optic sensors were used to validate the FEA model. These highly accurate sensors could not only determine the behaviour of the individual elements of the bridge but when used in series could evaluate the behaviour of the bridge holistically. By using the fibre optic sensors in this way the FEA model’s accuracy was confirmed and it could be used with confidence to aid the design process.

Abercorn Bridge was among the first projects in Northern Ireland to use a combination of lightweight aggregate concrete and BFRP reinforcement. The use of these material, over traditional materials, allowed for the strengthening of span 4 as opposed to its replacement.

Along with the strengthening of the bridge, concrete repairs were carried out on all four spans. The installation of a cathodic protection system on all elements of the structure ensured that the repairs will last for the required life span of the bridge as well as arresting any corrosion that may have initiated elsewhere.

Through the use of load tests, it was confirmed that the designed load carrying capacity of the repaired and strengthened bridge was achieved.

Although the load test, which had been undertaken to 44 tonnes, had confirmed the increased load carrying capacity of the bridge, it was recommended that an 18 tonne GVW weight restriction be imposed. This recommendation was due to the age, location of the structure and the real potential for the unknown historic overloading of the structure. Fatigue is a concern when reassigning a bridge’s weight restriction and is very difficult to account for with an unknown history of loading. This and a combination of the bridge’s intended remaining life lead to the weight restriction recommendation. The bridge was reopened (Figure 11) with a weight restriction of 18 tonne GVW after the completion of the works.

![Figure 11. Reopened Abercorn Bridge after Works Completion](image)

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REFERENCES