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THE CONDITION OF THE ABERFELDY FOOTBRIDGE AFTER 20 YEARS OF SERVICE

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ABSTRACT

Aberfeldy footbridge was a milestone in the development of FRP composites for construction when it was completed in October 1992. Whilst there are now longer FRP-decked bridges, the cable-stayed Aberfeldy bridge still has the longest span. It was something of a demonstration project for FRP construction, combining a pultruded GRP deck, towers and parapet system with aramid parallel-fibre cables. The bridge has now been in-service for close to 20 years in the Scottish Highlands, and during that time has received little maintenance. It is timely to return to the bridge and assess its durability. This paper describes the condition of the bridge, including its overall structural performance, the state of the GRP components, the performance of the parapet, and the structure's dynamic response. The paper provides lessons for the design of future FRP composites bridges and structures.

INTRODUCTION

The construction of Aberfeldy Footbridge was a milestone in the emergence of fibre-reinforced polymer (FRP) composites as structural engineering materials. Over the last twenty years FRP composites have become commonplace as structural strengthening and many FRP bridges have been built around the world. When Aberfeldy Footbridge was opened on 3 October 1992, applications of FRP in structural engineering were in their infancy (Hollaway, 2010). Whilst it was not the first FRP composite bridge, the construction of a cable-stayed footbridge with a 63m main span was substantially longer than any previous FRP bridge. It received numerous awards, such as the Saltire Award for Civil Engineering Design 1993. Whilst many FRP bridges have been built since, to the best of the author's knowledge, no all-FRP bridge has yet been built with a longer span.

The Aberfeldy Footbridge was a demonstration project that tested innovative technology. Like all such projects, it is vital to review how the structure has performed, to learn which innovations have worked well, and to feed this into the design of future FRP composite structures. This paper examines the performance of the Aberfeldy Footbridge after 20 years in service. It updates a previous paper that was written after 10 years in service (Cadei & Stratford, 2002).

An Overview of the Bridge

The Aberfeldy Footbridge crosses the River Tay at Aberfeldy in Perthshire, Scotland, and is shown in Figures 1 and 2. The cable-stayed bridge is 113m long, with a 63m main span, and back spans of 25m each. The bridge deck and towers are made from glass FRP (GFRP); the stay cables are Parafil aramid parallel-lay ropes, and the parapets are made from GFRP sections (Harvey, 1993; Lee, 1993). Apart from the aluminium connections required to attach the stay cables to the deck, the structure of the bridge is made completely from FRP.

The bridge connects the two halves of Aberfeldy Golf Club. The use of FRP materials was driven by the ease with which the bridge could be constructed. The lightweight components were erected by students from Dundee University without the need for cranes or other heavy construction plant, and this resulted in a far more economical bridge than would have been possible using traditional materials (Burgoyne & Head, 1993).



Figure 1. Aberfeldy footbridge from the south (December 2010).



Figure 2. Aberfeldy footbridge from the north (June 2008).

The bridge deck and towers were fabricated using components from the Advanced Composite Construction System (ACCS), a cellular modular construction system made from pultruded GFRP, shown in Figure 3. The bridge deck arrangement is shown in Figure 4. It has 3 GFRP planks across its width, with edge beams to provide stiffness. These longitudinal components are supported on primary transverse beams that connect to the cables, and intermediate secondary transverse beams (Head, 1994). The ACCS components were bonded together on site using an epoxy adhesive, with a toggle that provided mechanical interlock until the adhesive had cured.

The parapets (Figure 4) were fabricated from non-ACCS GFRP pultruded sections (which will be discussed in more detail below), and the bridge is surfaced using a former rubber conveyor belt.

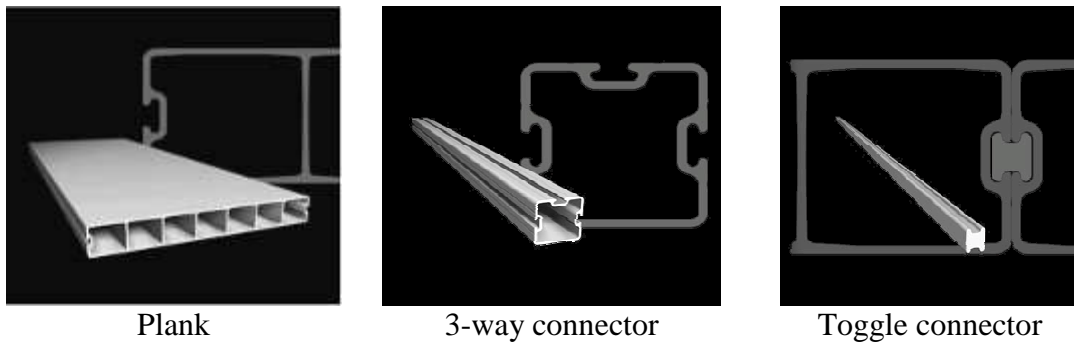


Figure 3. The ACCS components used in the bridge deck and towers.
 (ACCS was developed by Maunsell Structural Plastics and is now produced by Strongwell Ltd. as Composolite).



Figure 4. Aberfeldy footbridge from above and below the bridge deck (June 2008)

Strengthening of the Bridge in 1997

The bridge was designed to a 5.6 kN/m pedestrian live load, and was not designed for the concentrated loads that result from motorised traffic. Consequently, the bridge was overloaded when it was crossed by a small tractor towing a trailer of sand, resulting in cracks in the top surface of the deck components (Cadei & Stratford, 2002).

The bridge was strengthened during 1997 by bonding and rivetting GFRP plates onto the top surface of the deck (Figure 5). At the same time, the edge beams were strengthened to either side of each primary beam using prepreg CFRP sheets, to transfer the additional cable loads that would result from (for example) motorised golf buggies.



Figure 5. GFRP plates retrofitted to strengthen the bridge deck (June 2008)



Figure 6. CFRP strengthening retrofitted around a primary transverse beam (June 2008)

IN-SERVICE PERFORMANCE APPROACHING 20 YEARS

The team that designed and constructed Aberfeldy Footbridge has disbanded, and the bridge's owner (Aberfeldy Golf Club) does not have expertise in structural engineering or FRP composites. Consequently, the bridge's maintenance is best described as minimal, providing a useful case study into potential deterioration of FRP bridge construction. The condition survey below is based upon the author's visual inspections of the bridge during visits in 2004, 2008, 2010 and 2011 (indicated by the dates in the figure captions).

Overall Structural Performance

The primary structure of the bridge continues to perform well, with no visual signs of overall structural deterioration. Whilst a visual inspection will not detect every deficiency, FRP composites are brittle and hence structural deterioration usually results in cracks in the GFRP components. Careful inspections of the bridge deck have not revealed damage that is a result of structural deficiency, but impact damage has occurred that will be discussed below. The bridge deck has a smooth curve and there is no evidence of movement of the towers, deck, foundations or abutments. There are no slack cables, and there is no sign that the cables have pulled out from their anchorages (Figure 7).



Figure 7. Anchorage of a cable to the bridge deck (June 2008).

Dynamic Performance

Aberfeldy Footbridge is known for its lively dynamic response, due to its high live load (5.6 kN/m) to dead load (2.0 kN/m) ratio and slender proportions. Half of the dead load is ballast that was provided to improve the bridge's aerodynamic stability. The bridge was not, however, designed to meet the allowable footfall response specified by the Highways Agency (Highways Agency, 1988), due to the bridge's location on a private golf course (Cadei & Stratford, 2002).

The dynamic performance of the bridge was characterised in 1995 (Pimental *et al.*, 1995) and again in 2000 (Pavic *et al.*, 2000). These studies determined the natural frequencies and damping ratios shown in Table 1 and graphically in Figure 8. The natural frequencies of the bridge were determined by the author in December 2011, and are reported alongside the previous data. Adverse weather conditions (heavy sleet and a temperature only slightly above freezing) prevented sufficient data from being collected to determine the higher natural frequencies and damping ratios in 2011.

Table 1 – Dynamic response in 1995, 2000 (from Cadei & Stratford, 2002) and 2011.

Mode*	Frequency (Hz)			Damping ratio for empty structure (%)	
	1995	2000	2011	1995	2000
H1	1.00	0.98	0.93	-	1.0
V1	1.59	1.52	1.49	0.84	0.4
V2	1.92	1.86	1.77	0.94	0.7
V3	2.59	2.49	2.41	1.20	0.7
H2	2.81	2.73	2.58	-	1.2
V4	3.14	3.01	-	-	0.8
T1	3.44	3.48	3.39	-	5.5
V5	3.63	3.50	-	-	0.6
V6	4.00	3.91	-	-	0.9
T2	4.31	4.29	-	-	3.2
V7	4.60	4.40	-	-	0.8
V8	5.10	4.93	5.13	-	1.8

* V = vertical, H = horizontal, T = torsional

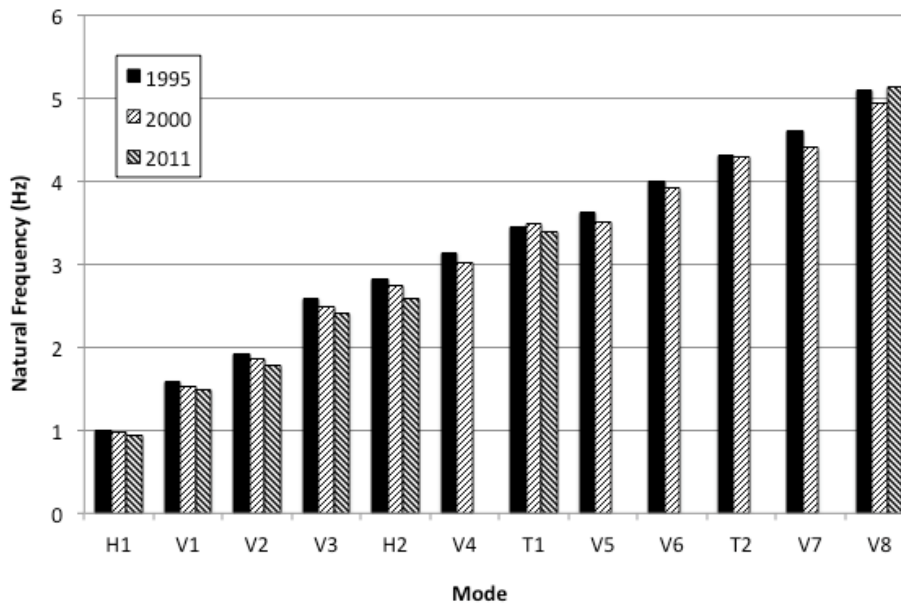


Figure 8. Dynamic response of Aberfeldy Footbridge in 1995, 2000 and 2012.

The reduction in natural frequencies between 1995 and 2000 was previously attributed to the increase in mass of the deck due to the strengthening work (Cadei & Stratford, 2002), but Figure 8 shows a further in the natural frequencies between 2000 and 2011. This could be attributed to an increase in mass of the bridge deck due to moisture absorption (GFRP can absorb up to 1.5% moisture by weight), or potentially due to reduction in the stiffness of the GFRP. It must be noted, however, that the 2011 values were obtained in winter, after a period of extended wet weather and cold temperatures. The moisture content of the GFRP will undergo seasonal variations and the bridge stiffness is potentially affected by temperature, consequently the reduction in natural frequencies cannot be taken as a conclusive indicator of structural performance.

Durability of the Primary Structural Components

The ACCS components used to form the bridge deck and towers incorporate a surface veil, which is an outer polyester fabric that traps a layer of resin at the surfaces of the pultrusion. This acts as a barrier layer to prevent moisture ingress into the body of the component, where it could result in degradation of both the glass fibres and the matrix resin (Holloway, 2010). The surface veil also provides UV and corrosion protection to the GFRP pultrusions. The ACCS components are in a generally condition; however, there are regions where the surface veil has been eroded away on the top of the edge beams (visible as a fibre texture at the top of Figure 9a). The surface veil erosion has been gradually increasing over the ten years since the previous paper (Cadei & Stratford, 2002).

The cut ends of ACCS components were sealed using adhesive to prevent moisture ingress along the fibres, and this seal appears to be in generally good order (Figure 9b). The adhesive joints between the deck components (Figure 9a) also appear to be in good order, with no evidence of the crazing or discoloration that accompanies degradation. There are some small chips in the ACCS components that have left the fibres exposed, but these are very few.

The aramid stay cable ropes incorporate a polyethylene sheath that protects them from moisture ingress and UV corrosion. The cables were over-wrapped where they joined with the aluminium anchorage to ensure protection, but this over-wrap has degraded, potentially leaving a path for moisture ingress into the critical anchorage detail (Figure 7).



(a) GFRP and adhesive joint condition on bridge deck



(b) The sealed end of a transverse beam

Figure 9. Durability of the bridge deck components (June 2008).

Mould, Lichen, and Moss Growth on the Bridge

The elevations of the bridge are greening-over, due to the growth of moulds, lichens and moss (Figure 10). The grooves and connections on the side of deck trap water supplies for growth. The growth is no more than would be expected on a timber bridge. Provided that it is a surface growth, this greening of the bridge will not affect the structural performance of the bridge, but it could exacerbate degradation where the surface veil of the components has occurred. There is very little growth where over the carbon strengthening around the primary transverse beams (Figure 6), due to fewer indentations that trap water, and due to the use of a resin that inhibits growth.



Figure 10. Greening of the bridge deck (June 2008).

Durability of the Parapets

The parapets consist of rectangular parapet posts, top and bottom rails, and closely spaced circular vertical members (Figure 4). These were all standard GFRP pultrusions, although they were not produced to the same specification as the ACCS deck components. The parapet components consequently exhibit greater erosion of the surface veil, with many regions of exposed fibres, particularly on the bottom rail due to a combination of abrasion and weathering.

The parapet posts pass through the deck, and were doweled beneath the deck (Figure 11) and bonded to the top of the deck. The top and bottom rails are connected to the parapet posts by means of a sleeved plate that passes through the post (Figure 12). This arrangement was designed to accommodate movement

of the parapets as the bridge flexes; the sleeved plate was intended to provide damping through friction and hence improve the dynamic response of the bridge. The post-to-deck and rail-to-post connections have all worked loose, and there is considerable movement of the parapet components as the bridge flexes, but very little friction. Some top rail connections have become completely detached (Figure 12), and rudimentary repairs have been effected using screws and zip ties (Figure 13).

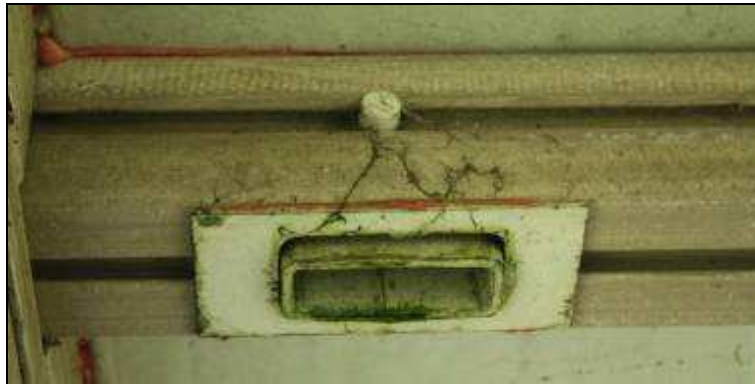


Figure 11. Connection of the parapet post beneath the bridge deck (June 2008).



Figure 12. Details of the connection between the top handrail and parapet post (June 2008).



(a) Screw repair (June 2008)



(b) Zip tie repair (December 2011)

Figure 13. Parapet maintenance solutions

Impact resistance

Impact damage is the most serious threat to the durability of the Aberfeldy Footbridge. There are a number of instances of impact damage to the bridge, equating to significant structural damage, as well as exposing the glass fibres to environmental degradation.

Figure 14 shows the most substantial impact damage, on the north back span, which has penetrated the lowest 3-way connector component. The damage is located mid-way between primary transverse beams, and consequently is unlikely to threaten the bridge's performance; however, it obviously results in a local loss of strength and allows environmental degradation of the GFRP.



(a) Location of the damage (June 2008)



(b) Detail of the damage to the bottom 3-way component (December 2011)

Figure 14. Damage on the east elevation of the north back span.

Another example of impact damage to the underside of the deck is shown in Figure 15, while Figure 16 shows that an aluminium angle has been added to protect (or possibly repair) the underside of the deck adjacent to the south tower. Fixing this angle using screws is not ideal, as it is likely to result in splitting between the glass fibres, resulting in accelerated degradation of the GFRP.

In 2002, the base of the parapet posts were noted to be 'badly scuffed' (Cadei & Stratford, 2002). Figure 17 shows how after another ten years service, the base of some posts are now severely damaged, with substantial loss of section due to impact and abrasion. These posts require repair, and should be protected using a kick board. Separate impact protection has also been added to the northern end of the parapets (Figure 2).



Figure 15. Impact damage to the underside of the deck (December 2010).



Figure 16. Impact protection applied beneath the deck (December 2010).



Figure 17. Impact damage to the bottom of a parapet post (December 2011).

CONCLUSIONS

Aberfeldy Footbridge was an exemplar demonstration of FRP composite construction in 1992, and it remains so in 2012. The primary structural components (GFRP deck, GFRP tower and aramid cables) perform well, with no obvious degradation in performance. The natural frequencies of the bridge have reduced slightly over the last twenty years, but it is not possible to determine whether these are due to changes in the structure or seasonal changes in environmental conditions.

Whilst the primary structural performance is good, there are a number of details that have not performed so well. The most obvious are the parapets, which were designed to move with the bridge, but have failed at the connection details and in some cases have become detached. The most serious threat to the bridge, however, is due to impact damage. Impact damage has resulted in substantial local sectional loss in the bridge deck and parapet posts. This requires repair to restore the sectional strength and to prevent moisture ingress that will cause degradation of the GFRP sections.

Elsewhere on the bridge there are numerous regions of exposed fibres, which if left unchecked could result in accelerated degradation of the GFRP. The parapet rails are particularly badly affected, but the surface veil layer has also eroded due to weathering along the top of the deck edge beams. These regions should be cleaned, dried and sealed with a suitable resin to halt moisture ingress. Moss and lichens grow on the elevations of the bridge, which might be prevented by a different choice of resin. This growth is only of aesthetic concern so long as the surface veil remains intact on the GFRP components.

These details are relatively straightforward to repair, together with preventative maintenance such as cleaning the deck and replacing the over-wrap layer that protected the connection between the aramid stay cables and the aluminium anchorages. However, the bridge receives minimal maintenance by a non-expert owner. Where repairs have been conducted, they have used traditional techniques such as screwing into the GFRP components, and there is a danger that this could cause long-term damage to the GFRP.

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