The British Dam Society

Valve Tower GRP Lining - Llyn y Fan Fach Refurbishment

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SYNOPSIS A Section 10 inspection on Llyn y Fan Fach dam led to MITIOS, one of which was to arrest the structural cracking and eliminate leakage into the draw-off shaft. This paper covers the investigation that was done into the causes of cracking, including finite element modelling; the different options that were looked in to, such as decommissioning, demolition and rebuild, less intrusive repairs and structural lining, and why the chosen solution was lining the tower with a structural FRP liner and its design. The paper then looks at the construction, including procurement, delivery, installation and how it functions in place.

INTRODUCTION

Llyn y Fan Fach is a reservoir at the head of the Afon Sawdde, located within the Bannau Brycheiniog National Park (Figure 1). Constructed between 1914 and 1919 by conscientious objectors it raised the original lake by approximately 3m. The spillway for the reservoir is via a 6.1m ogee weir in the centre of the main dam. This discharges into a masonry and concrete stilling basin and spillway channel before flowing freely into the Afon Sawdde. The reservoir was previously used to supply water to a treatment works downstream, but is now used to provide compensation flows to a fish farm that was created at the same location as the treatment works.

Figure 1. Llyn y Fan Fach Reservoir

Managing Risks for Dams and Reservoirs

Alongside routine maintenance, a Section 10 Inspection under the Reservoirs Act 1975 was undertaken on 15th October 2019. The inspection report stipulated the following Measures in the Interests of Safety (MITIOS):

- To arrest the structural cracking and eliminate leakage into the draw-off shaft. This shall be in the form of a new structural liner to the valve shaft and sealing of the existing structure.
- The spillway apron and vehicle crossing shall be reconstructed to safely convey the safety check flood.

The MITIOS also acknowledged that the dam could also be discontinued.

Key participants

- Client: Dŵr Cymru Welsh Water (DCWW)
- Main contractor: Morgan Sindall Infrastructure (MS)
- Consultant designer: Arup
- Mechanical contractor: Whitland Engineering Ltd
- GRP liner: iLine Technologies Ltd
- Precast concrete: FLI Precast Solutions Ltd
- Formwork: Cordek Ltd (using Filcor 90)
- Shuttering support: PERI UK
- Concrete repair: Beton Bauen Ltd
- Underwater survey/repairs: Edwards Diving Services
- Over pumping: Pump Supplies

FEASIBILITY DESIGN

As the Project progressed through feasibility several options were considered, one of which was the discontinuation of the reservoir and restoring the area back to its original state.

It became apparent that there were several constraints associated with discontinuance. Although the reservoir is not in public supply, there is an agreement in place to provide water to private stakeholders downstream. Separately DCWW was notified that CADW had placed an interim Grade II listing on the dam structure and other curtilage structures. Interim designation was issued in February 2021, with full Grade II listed status designated in February 2022.

Following the feasibility assessments, DCWW's collaborative Risk and Value Process was followed which showed the preferred option to be the refurbishment of the dam, which included works to the draw-off shaft and spillway.

TOWER REFURBISHMENT

Investigation into cause of valve tower cracking

An initial investigation was undertaken to determine the most likely driver of the cracking so that a suitable and effective solution could be implemented that would stem any future leakage and deterioration of the structure.

There are records of the cracks that go back to 1965. These were repaired in 1980, and a report in 2010 noted that three dominant cracks were suffering leakage. An inspection report in 2019 speculated that freeze-thaw action and temperature variations led to the cracking of the structure. A 3D scan of the valve tower interior was undertaken in 2021, which was used to inspect the location and extents of the cracking (Figure 2)

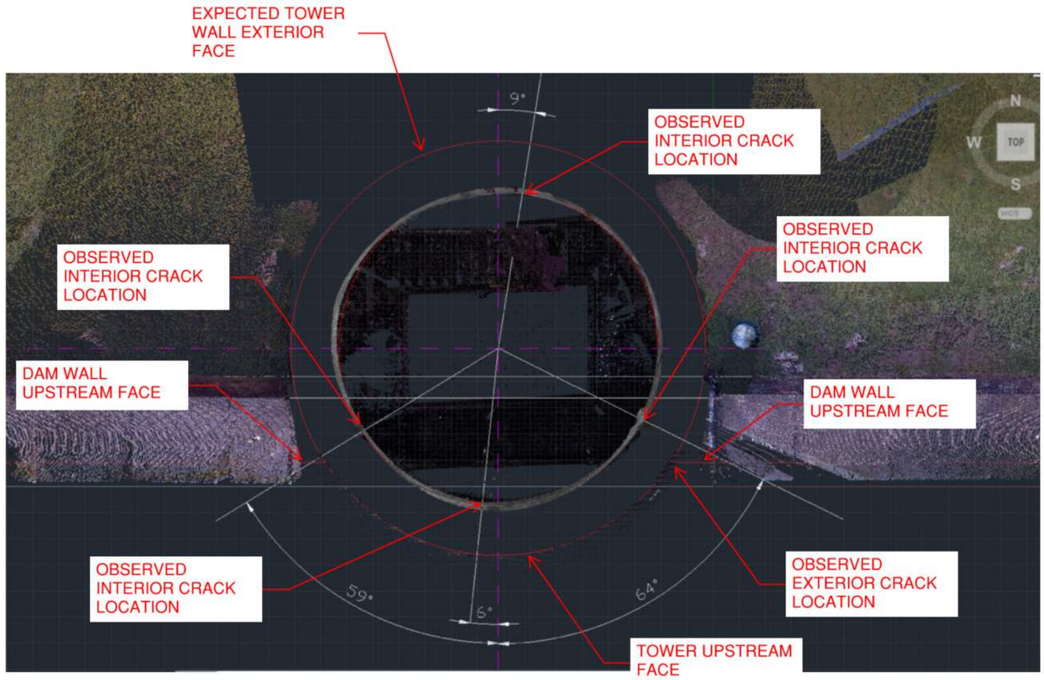

Figure 2. Observed locations of leaking cracks in valve tower wall

Assessing the likely causes of cracking in the assumed unreinforced gravity structure led the team to hypothesise that cracking has originated due to volumetric changes in the adjacent dam walls exerting pressure on the valve tower.

A finite element model of the structure was built to provide supporting evidence for this hypothesis. Volumetric change was considered in the longitudinal axis of the dam wall only, and the investigation acknowledged there were limitations to the analysis. These limitations were acceptable as the analysis was only used to demonstrate locations in which tension stresses were being developed. The structure was first analysed with 1D elements, based on the results the zones in Figure 3 should be presenting cracking:

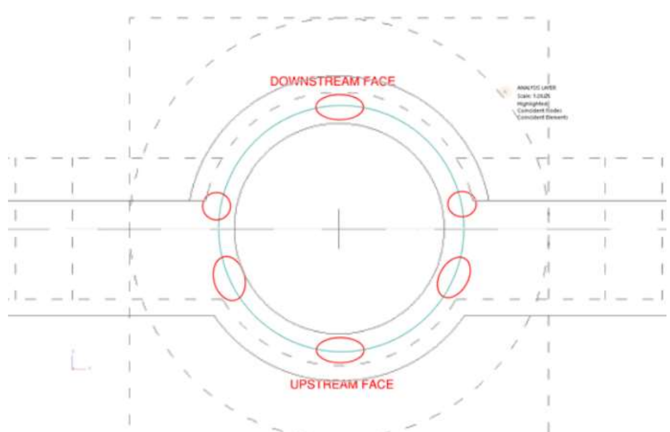

Figure 3. Crack locations predicted by 1D analysis

Managing Risks for Dams and Reservoirs

For further investigation, a 2D analysis was undertaken in GSA and similar results were found but show more detail on the location and development of the stresses (Figure 4).

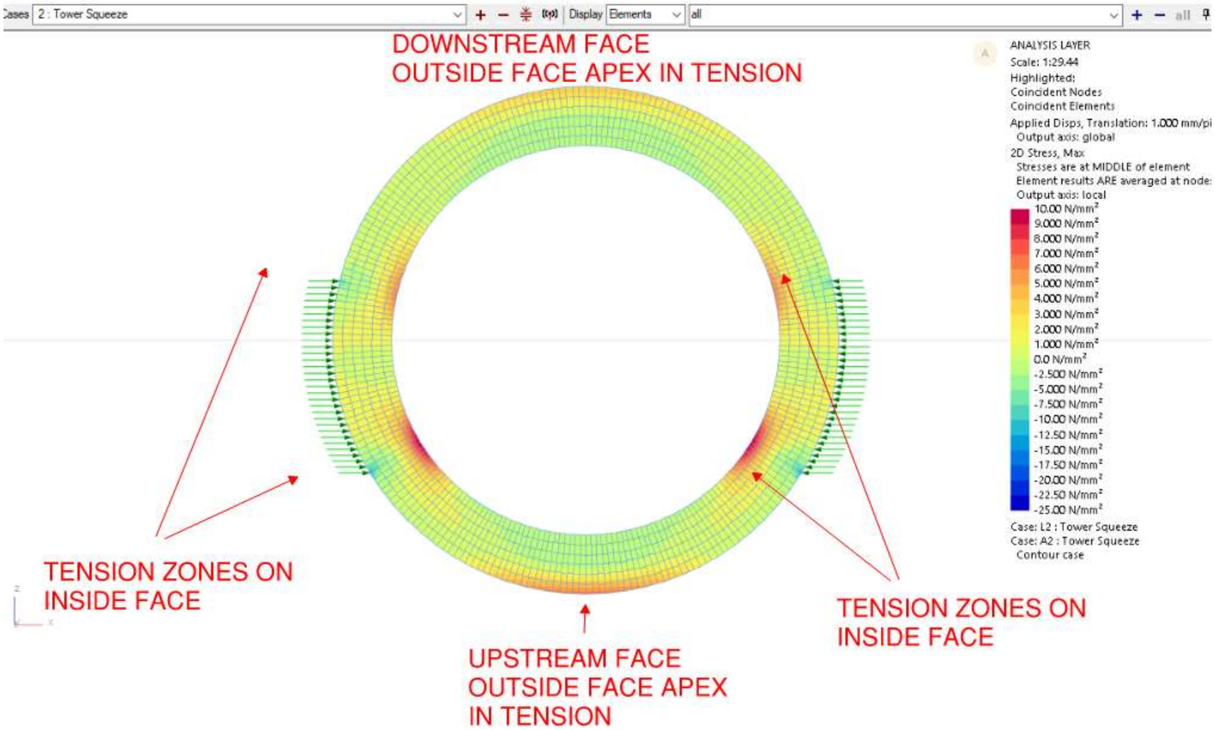

Figure 4. 2D Stress results for dam wall expansion

Comparison with the results of the model and the point cloud data concluded that there was significant evidence that volumetric change of the dam walls that connect to the valve tower was inducing tension stresses in the shaft walls causing cracking. Tension areas predicted by models of this action correlated well with the observed real-world cracking.

It is also possible the cracking was contributed to via differential lateral movement of the dam wall and valve tower under the cyclic operational loading as a secondary driver.

The acceleration of leaking in the most recent years may be due to exacerbating factors associated with the cracks fully penetrating the section, such as the water inflow washing out fines, freeze-thaw action occurring in and around the newly exposed faces of the cracks, and debris ratcheting the open cracks preventing them from closing.

A solution was then developed to mitigate the leaking and protect the structure against further deterioration.

Proposed Solution

GRP Liner

A full height liner made from a designed GRP material. A void was left between the GRP liner and the existing tower to allow for installation tolerances and this void was filled with a cementitious grout. The liner was a full annulus piece with no penetrations that would allow water ingress. Fixings were built into the liner to accept connections from the internal access staging that is required in the permanent case. The GRP liner was designed to withstand the full lateral pressures. GRP has some inherent flexibility that allows the dam wall to continue to expand and contract, with the liner designed for the expected movements.

External Concrete Facing

A reinforced concrete structure on the external face of the valve tower. A post-fixed anchor system was used to tie it back to the existing dam wall on either side of the valve tower. The concrete was not bonded to the existing concrete but separated by way of a membrane. A movement joint was provided at the apex of the arch so that stresses due to thermal movement of the dam wall are not transferred into the new structure. This is important as preventing the thermal movement from happening is not feasible, so instead mechanisms for this to occur without causing damage were provided.

The following are the possible failure mechanisms which were addressed by the design:

- Lateral Hydrostatic Pressures – to be resisted by the GRP liner, replacing the structural requirement of the existing concrete to resist hydrostatic pressures from the reservoir. For robustness the external concrete casing was also designed to resist hydrostatic pressures independently of the GRP structure.
- Lateral Embankment Pressures - existing downstream arch continues to perform structurally.
- Thermal Actions – existing cracks continue to act as movement joints eliminating stress build-up due to thermal actions in the existing structure. The GRP liner designed to deform with the tower elastically. The external concrete casing structure has a movement joint to alleviate these stresses.
- Environmental Attack - cracks raked out and sealed with a flexible sealant to allow the existing concrete to move under thermal strains and keep the cracks free from obstructions that could lock the joint and cause ratcheting actions to widen the crack. The new concrete casing insulates the cracked areas from further environmental deterioration.
- Upstream Arch Stability - instability caused by actions external to the valve tower, e.g. hydrostatic or wind loads, are transferred to the GRP liner. The structural cases that the existing cracked concrete used to perform have been replaced by the new structures and the existing concrete no longer has any structural purpose. To prevent the cracked concrete from instability it is restrained on either side by the new GRP liner and the new external concrete casing.
- Seismic Loads - the external concrete casing structure and GRP liner was designed to resist loads due to seismic actions. The seismic loads were analysed in a pseudo-static manner. The loading on the two structures was due to a ground acceleration identified as PGA = 0.15g acting on the loose cracked concrete mass, self-weights, and retained reservoir water. The reservoir water level considered was top water level.
- Accidental Construction Loads - the contractor managed stability during construction.

A robust approach to the design of this external structure was adopted where both the GRP liner and the external structure were designed ignoring favourable effects from one another, i.e. both structures were designed to resist hydrostatic, hydrodynamic and seismic acceleration loads (Figure 5). In the case of the GRP liner, these loads were defined and communicated to the GRP supplier for design, which was in turn checked by Arup.

In the case of the external casing structure, it was as a horizontal cantilever fixed back to the dam wall with post-fixed fasteners. It was designed to resist the cracked concrete from displacing during a seismic event in one direction and to resist hydrostatic and hydrodynamic forces in the other. The structure was modelled as a 2D shell in FEA software with the anchors as pin supports.

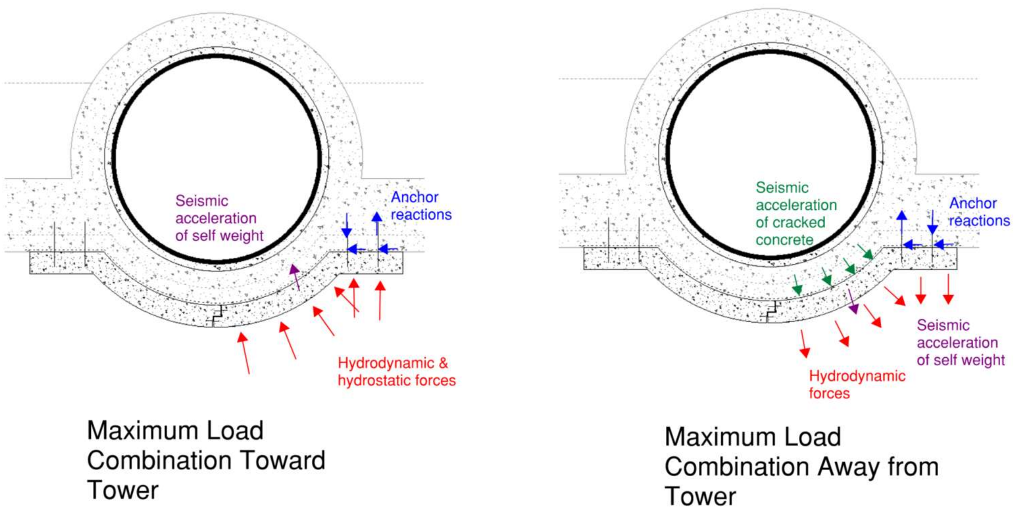

Figure 5. External structure load cases

OTHER WORKS

Spillway Replacement

The proposal was to fully replace the lower spillway with a precast structure capable of passing the 1,000yr (design) and 10,000yr (safety) flood events for the Category B dam. The wall heights were designed to contain the flows including full USBR freeboard. In order to maintain cultural heritage of the existing spillway, the spillway was lined with stonework.

Consenting – LBC, BNG, SSSI/SAC, Macrophyte

The dam is located within the National Park, a Site of Special Scientific Interest (SSSI), Special Area of Conservation (SAC) and is a Listed Building, therefore consenting was a significant constraint on the works.

Proactive interaction and timely submission of the Listed Building Consent (LBC) application minimised programme impacts. As part of this consent a biodiversity net gain (BNG) enhancement scheme was undertaken to help improve the local environment and offset the impact of the works, which saw the planting of over 200 new trees and the installation of a dipper box by the main watercourse.

Separately a SSSI assent was submitted to NRW to support the works and ensure acceptable management was undertaken. In addition to common protection and standard methods, a rare macrophyte was identified in the reservoir that was monitored and resurveyed post works to confirm the impact.

DELIVERY

It was clear that constructing this scheme was going to be challenging due to the site constraints, including remoteness, narrow access roads, SSSI areas, National Park status, listed structures, bridge weight limits and popularity of the location with members of the public. From the main site office to the working area there was a 240m altitude difference over the 2.4km access road.

Due to the site location, opportunities for off-site fabrications were pursued to minimise the challenge of getting fresh concrete to the working area. Due to the distance from the concrete batcher, narrow access roads and having to offload concrete for transportation to the dam, it would take nearly two hours to get concrete to the workface.

A significant constraint was the low clearance and low capacity bridges on approach to the site. This restricted the size of plant that could be transported to site and, in turn, the size of components that could be handled. Therefore, a large number of precast concrete units were required to make up the spillway structure with a considered and minimised use of in situ stitches. Another example where this constraint influenced delivery was that the tower required GRP sections with a 2.7m internal diameter being transported over a 2.4m wide bridge. The rings were therefore formed in half sections and assembled in-situ (Figure 6).

Figure 6. Installation of GRP Lining

The use of prefabricated products gave the additional advantage of reducing site risks from concrete washout, excess materials, reduced potential quality issues, minimised working at height and reduced the amount of plant to be transported to the working area. This also helped to reduce the overall programme compared to if conventional methods been used, and had a positive effect on minimising the construction impact and carbon footprint on the project.

The site team utilised Filcour90 from Cordek expand polystyrene shuttering (Figure 7) to make the external repairs to the drawdown tower and dam face. This innovative shuttering solution used the output from 3D surveys to fabricate the intricate curvature of the existing tower and corbel detail and then mould the shuttering off site, allowing delivery to site in manageable sections. Given the location of the dam, with the poor weather conditions at times which the site team faced, traditional timber shuttering would not have been able to form the shape of the tower.

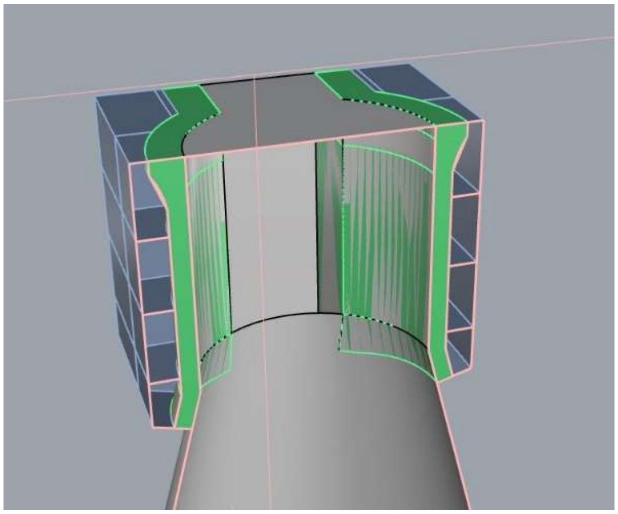

Figure 7. 3D external formwork

Demolition and reconstruction of the spillway was the most critical aspect of the project due to the inherent risks on the dam structure from scouring if it were to spill during construction (Figure 8). Water levels in the reservoir were lowered to provide a minimum storage capacity for a 1 in 150 year storm event as was stipulated by the Welsh Water Dam Safety Team and the QCE. To ensure that water levels were managed in the reservoir throughout the scheme, a temporary storm pumping system was established using 12" electric pumps. The pumps were located on floating pontoons on the reservoir to keep them off the reservoir bed to avoid silt issues. Due to the criticality of the works, a Dam Safety Construction Management Plan was developed to control any increased risk to the safety of the dam during construction. Duty - standby pumps and generators were installed with auto-changeover facility and telemetry systems that automatically called personnel in the event of an issue.

Figure 8. Spillway construction and lining

Under normal operating procedures the water from the reservoir was drawn off using a submerged siphon pipe which passed through the draw off tower, tunnel and down the mountain. The first valve on the siphon pipe, located in the tower, had to be replaced requiring our specialist diving contractor to install a temporary blanking plate within the reservoir to stop flows in the pipeline., An additional temporary over-pumping set up was installed to maintain the required flows down the mountain to supply the local fish farm. Isolating flows enabled the removal of the existing valve and replacement with two new units and pipes and subsequent re-commissioning of the siphon pipe. Remote operated vehicles were used to minimise manned diving and also to prove isolations before anyone entered the water. All diving works were closely managed with the site management and Client representatives by operating under “gold command” which provides detailed planning and scrutiny of all activities to always ensure the safety of personnel.

CONCLUSION

The use of the GRP liner has provided a robust, corrosion resistant solution to arrest the structural cracking of the tower, providing a flexible solution that will withstand both the varying seasonal conditions at the site and the extreme load-cases that it could be subjected to (Figure 9).

The remoteness of the site and access provisions at Llyn y Fan Fach were challenging, so the prefabricated GRP liner solution provided significant constructability advantages over traditional materials such as in-situ concrete. A similar approach could be considered for other applications in future schemes.

Figure 9. GRP Lining Installed

The scheme was completed in two phases from July 2022 until late December 2022 and from May 2023 to September 2023 and delivered successfully on time. Completion of the scheme has now provided DCWW with an asset that can be operated for many years to come and has enabled the statutory obligations under the Reservoirs Act 1975.to be closed off.

Managing Risks for Dams and Reservoirs

Throughout the scheme there were no reported accidents or injuries and a great safe working and positive intervention reporting culture was clear to see. 'How Are We Doing' feedback was obtained through the project from DCWW and received excellent comments.

The scheme has also now been signed off as achieving Perfect Delivery by Welsh Water which is a testament to the hard work and professionalism shown throughout all stages of the project.