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TECTON BUILDINGS (DUDLEY ZOO)

(Long Term Monitoring of Like-for-Like Repairs – Assessment in 2020)

1. Introduction and Background

A group of thirteen reinforced concrete structures were built in the period 1935 to 1937 at Dudley Zoo (DZG) by the Tecton Partnership, led by Berthold Lubetkin. The condition of the reinforced concrete had been slowly deteriorating over the past few decades. DZG was successful in being awarded an HLF grant in 2013 and the repairs and conservation started towards the end of 2013. The first building to be conserved was the shop, which was subsequently turned into an entrance hall. The second building was the original entrance gates which was retained to provide a 'front' for the zoo. Both of these buildings were successfully repaired and conserved. The next Tecton buildings to be repaired were the Bear Ravine and the associated kiosk. The Bear Ravine had been derelict for many years and was in a very poor condition with extensive decay of the reinforced concrete. This building was successfully completed in 2014. Finally, the Meerkat enclosure was repaired and conserved in 2015.

In order to monitor the long-term performance of the like-for-like concrete repairs, RTL was asked by Historic England to undertake monitoring of the repairs (and adjacent original concrete). Monitoring mainly used NDT techniques, although drill samples (for subsequent laboratory analyses) were taken in 2014. A significant amount of images have been taken so that repaired and original concrete surfaces could be suitably identified in future years. This monitoring programme was initiated in 2014 and the testing is likely to go on for a number of years to inform future repairs to historic concrete and that the repairs do not result in decay to the adjoining (original) concrete by a process termed 'the incipient anode or halo effect'. Monitoring points (stainless steel connections to the embedded steel reinforcements) were made on repaired areas on both the Bear Ravine and also on the Meerkat Enclosure to assess for this effect .

2. Site Visit (Kiosk and Bear Ravine)

The sixth annual site visit was made to Dudley Zoo on the 9th December 2020. The work entailed assessing the visual condition of the repairs and taking corrosion rate measurements on both the Bear Ravine and the Meerkat enclosure. The weather was cold (6°C) and dry on the day but the previous few weeks had been very wet. One thing that was obvious to all buildings was that the concrete surfaces (parent and patch) showed significant moss growth.

Visual Assessment – The kiosk was visually assessed. The repairs were still in a very good condition and no significant cracking or delamination was noted in the repaired areas, Figure 1. There was a fine crack on the top counter to the kiosk leading out from a steel column, Figure 2. This had not been noted previously and appeared to be some form of shrinkage crack emanating out from the embedded steel post.

The Bear Ravine was visually assessed and from a distance this also looked to be in a good condition after six years exposure after the repairs, Figure 3. However, there were a few problems noted previously when the repairs were examined in detail. Shrinkage and sometimes moss growth (in the cracks) was noted in a few areas of the top balustrade rail on the 1st floor (shown in previous reports). Cracks were also identified in some of the corners of the balustrade plates, most possibly due to thermal movement between the repairs and the parent concretes. Shrinkage cracks were also noted to the areas of repairs on the balustrade on the ground floor. Cracking to the circular columns was also noted at the Bear Ravine. All these defects were first identified in 2017 (some 3 years after the Bear Ravine had been completed) but they do not appear to have worsened.

In addition, three new cracks were noted to the repaired parapet wall to the prow of the Bear Ravine, Figures 4 and 5. A shrinkage crack was also noted to a square repair patch to the fluted section of the 1st floor wall, Figure 6. This defect is almost certainly old and is most probably due to the thin section repair carried out on this particular section of the wall.

The patch repair to test areas 1 and 3 at the Bear Ravine had suffered problems soon after they had first been installed in 2014, Figures 7 and 8. Both areas had reportedly been repaired using a lightweight repair mortar (Renderoc) following instruction from HE/RTL, whereas the other two test areas (2 and 4) had been repaired using like-for-like concrete to closely match the original concrete - as were all of the other patch repairs to the Bear Ravine.

A visual assessment of the underside of the prow (where carbon sheeting had been fitted to provide strength to the floor) showed no obvious defects.

Corrosion Rate Measurements- Corrosion rate measurements were taken of the embedded steel reinforcements within, and around, the four test areas in both the new and original concrete on the Bear Ravine. A schematic of the test areas at test sites 3 and 4, shows where the measurements were made, Figure 9.

Prior to the repairs being made, stainless steel threaded bars were attached (screw fitted) to the existing steel reinforcements. This <u>direct</u> electrical connection enabled both potential and corrosion rate measurements to be made (within the body of the concrete) after the repairs had been completed. A Linear Polarisation Resistance Measurement (LPRM) electrochemical monitor was used to take the NDT corrosion rate measurements on the repaired wall at the top of the bear ravine. The results are shown in Table 1.

Table 1

Corrosion Rate Measurements (μm/yr)

Location	Area 1	Area 2
1 Repair	0.92	2.16
2 Left - original	0.18	0.40
3 Right - original	0.39	0.26

Location	Area 3	Area 4
1 back left on original	0.44	0.29
2 back centre under repair	0.33	0.45
3 back right on original	0.33	0.23
4 top left on original	1.21	1.59
5 top centre on repair	0.67	1.40
6 top right on original	0.80	1.06
7 front left on original	0.73	0.52
8 front centre on repair	1.35	0.41
9 front right on original	0.66	0.70

All of these results were much lower than those found in previous assessments (2018 and 2017) and significantly lower (approximately 5 to 10 times) than those taken in 2016. Some of this decrease in corrosion rate may be associated with the decreased environmental temperature experienced in December (the previous assessments were made in the summer periods). However, it is also likely that the cleaned embedded steel has now established a protective oxide film on the rebar surfaces (through the zinc painted surfaces). Note - corrosion rates below 5 micrometers/year (which they all are) are considered to be insignificant. Note – 5 micrometers/year is 0.5mm in 100 years. Total corrosion loss in excess of 2mm would be required to delaminated concrete surfaces.

There does not appear to be any indication of 'increased corrosion activity' of the original concrete adjacent to the repairs, indicating that the 'incipient anode effect' is not affecting these repaired areas of concrete. This is probably to be expected as this type of deterioration has only ever been noted by the author where the concrete has been contaminated with chloride salts (marine or de-icing salts). However, a visual assessment of repairs 3 and 4 showed that the repair to area 4 showed significant cracking and shrinkage.

Hammer Surveys - Schmidt hammer testing was carried out on five typical repairs to the Bear Ravine. The average surface strength readings of the repairs were 36N/mm^2 whereas those of the adjacent parent concretes were 38N/mm^2. A concrete strength of 35 N/mm^2 is generally taken to differentiate between low and average quality concrete and above 50 N/mm^2 indicates high strength concrete. The surface strengths of both the parent and patch concretes may therefore be considered as of low average strength.

3. Site Visit (Meerkat Enclosure)

Visual Assessments – A visual assessment of the Meerkat enclosure showed no signs of either cracking or shrinkage of any of the repairs, Figure 10. The Meerkat enclosure was completed after the Bear Ravine, and it may be that the Dudley Zoo repair team simply improved their application process as they progressed with the repairs to the Tectons. Views of some of these repairs are shown in Figures 11 and 12 and they show that the repairs are now blending in with the parent concretes following five years of weathering.

The repairs were fully completed on this structure in early 2016. 4mm stainless steel threaded bars were mechanically attached to four of the existing steel reinforcements so that measurements could be taken both in the repaired areas and also on original concrete, Figure 13. An image taken of this area of the enclosure in 2020 is shown in Figure 14. Again, this shows that these patch repairs are almost fully blended in with the parent concretes.

*Corrosion Rate Measurements- C*orrosion rate measurements were taken of the embedded steel reinforcements on the top surfaces which included the repairs, the parent concretes and also the interface (where the insipient anode effect may be operative). The results are given in Table 3.

Table 3

Corrosion Rate Measurements on Meerkat Enclosure (µm/yr)

Location	Repair	Original	Interface
1 Area 1	0.03	0.05	0.06
2 Area 2	1.26	0.98	0.64
3 Area 3	1.60	0.17	0.56
4 Area 4	0.87	0.22	0.45

Again, corrosion rates of the repairs were lower than those measured in previous visits. This may be due to the lower environmental temperature in December 2020 but also that the steel should now have developed a protective oxide film on its surfaces. There did not appear to be any clear indication of 'increased corrosion activity' of the original concrete adjacent to the repairs, indicating that the 'incipient anode effect' is unlikely to be affecting these repaired areas.

Hammer Surveys - Schmidt hammer testing was carried out on five typical repairs to the Meerkat Enclosure. The average surface strength readings of the repairs were $32N/mm^2$ whereas those of the adjacent parent concretes were $33N/mm^2$. The surface strengths of both the parent and patch concretes may therefore be considered as of poor strength.

4. Discussion and Conclusions

The corrosion rates of the repaired concretes for both Tecton structures have now decreased to a very low level and much less that the 5µm/yr which is considered to be significant. This appears to be a consequence of the lower environmental temperature experienced in December 2020 but also due to the formation of a protective oxide film on the steel reinforcements.

The hardness values of the concrete in the repaired areas of both Tecton structures will now have reached their maximum values. This shows that both the parent and patch concretes are similar and have surface strength values in the average to low range.

Visual assessments of the repairs have shown that there are some cracking and shrinkage problems associated with the Bear Ravine; the other Tectons appear to be free of such defects. These defects may have been due to application problems when they were originally repaired. Repairs carried out later on for the Meerkat Enclosure showed no similar problems.

It is possible that the water ratio of the repair mix was too high when the work was first started, leading to shrinkage. Although the author gave outline recommendations for these repairs in 2013, it is not clear if these were closely carried out. These include minimising the water cement ratio, roughening the back of the breakout, dovetailing the sides of all repairs (using an undercut of 2 to 3mm) and providing additional stainless steel cramps is some areas if steel reinforcements were absent. These defects will need ongoing monitored to check that the underlying steel reinforcements do not start to corrode.

The corrosion rate monitoring of the repaired areas did not give any indication that the incipient anode, or halo effect, was occurring. This is not particularly surprising since these concretes generally contain low levels of chlorides within their body and are not subject to either marine exposure or have de-icing salts deposited on their surfaces.

Dr David Farrell
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17th December 2020

Figure 1 View of the repaired Kiosk after 7 years exposure.

Figure 2 Fine crack leading out from the steel column, most probably due to shrinkage of the repair concrete.

Figure 3 View of the repaired Bear Ravine after 6 years exposure.

Figure 4 Cracks noted to the repaired parapet wall to the prow of the Bear Ravine. Note also the moss growth established in the fine shrinkage cracks to the upper balustrade rail.

Figure 5 Another crack noted to a repaired parapet wall to the Bear Ravine.

Figure 6 Classic shrinkage cracks noted around a square repair to the fluted section of the 1st floor wall.

Figure 7 View of the small patch repairs (1 and 2) on the outer wall at 1st floor level. Patch 1 was made using a proprietary repair mortar and patch 2 was made using a like-for-like concrete repair.

Figure 8 View of the small patch repairs (3 and 4) on the inner wall at 1st floor level. Patch 3 was made using a proprietary repair mortar and patch 4 was made using a like-for-like concrete repair. Note – shrinkage and moss growth (in cracks) for patch 4.

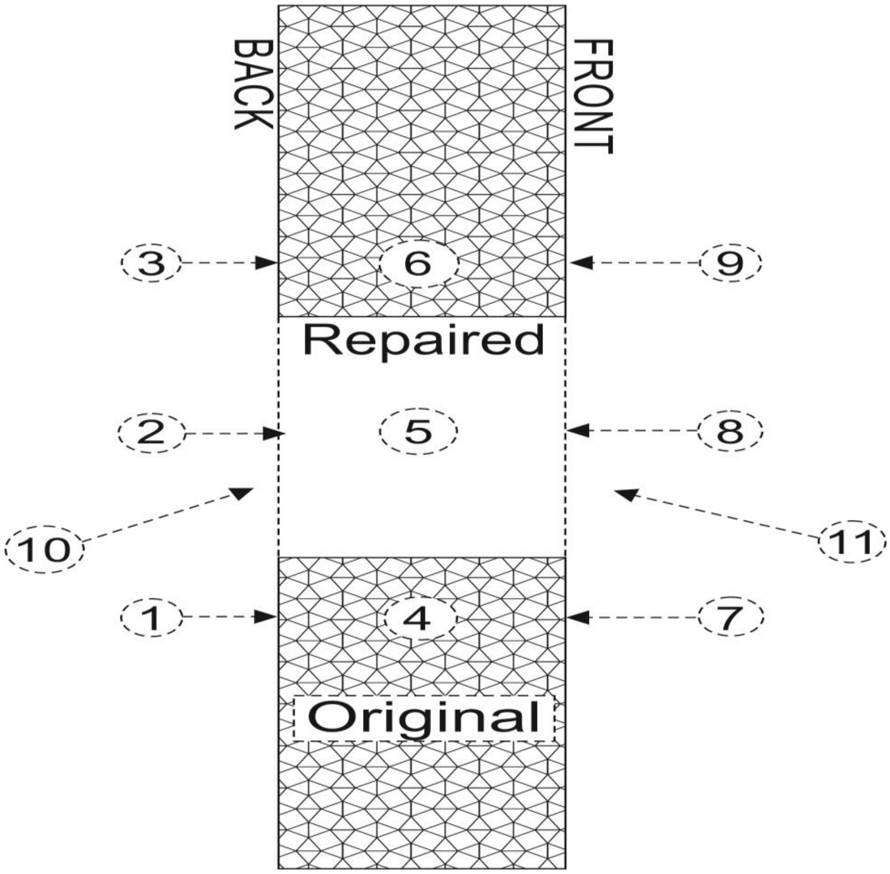

Figure 9 Locations where corrosion rate readings were taken in test areas 3 and 4 of the Bear Ravine 1st floor wall.

Figure 10 View of the repaired Meerkat Enclosure taken 5 years after completion.

Figure 11 The repairs to both the top section and vertical fluted section are now blending in with the parent concrete.

Figure 12 Another view of a repaired section (horizontal and vertical) which is also starting to blend in with the parent concrete.

Figure 13 Broken out section at the back of the Meerkat Enclosure (2015 - prior to repairs) showing the four stainless steel test points (right front and left back) attached to the different rebars.

Figure 14 View of the repaired top of the wall showing it almost fully blending in after 5 years exposure.